INDUSTRIAL ELECTRICAL MEASURING INSTRUMENTS

INDUSTRIAL ELECTRICAL MEASURING INSTRUMENTS

BY

KENELM EDGCUMBE

M.Inst.C.E., M.I.E.E.

FULLY ILLUSTRATED

SECOND EDITION, REVISED AND ENLARGED

LONDON

CONSTABLE & COMPANY LTD

10 ORANGE STREET LEICESTER SQUARE WC

1918

NEW YORK

D. VAN NOSTRAND COMPANY

EIGHT WARREN STREET

Printed in Great Britain

PREFACE

In the interval which has elapsed since the publication of the First Edition, there has been considerable development in nearly all directions. Of epoch-making innovations there has been none, but progress has been continuous. As a result, it has been necessary to rewrite the whole, and the expansion of all sections has been so great that in order to keep within reasonable limits some have had to be abandoned. For this reason, the subject of "Fault Localisation," as distinguished from "Fault Detection," has been omitted, as have also "Relays" and "Over Pressure Devices." "Pyrometers," on the other hand, have again been dealt with at some length.

The success attending the First Edition appeared to warrant a continuance of the same method of treatment, which has accordingly been followed. Thus, it will be found that the mathematics is of the simplest, vector diagrams being used wherever possible, and in this connection the following paragraph may be quoted from the Preface to the First Edition :—

"Mathematicians will doubtless deplore the almost entire absence of mathematics, but, writing as an engineer, for engineers, the author is strongly of opinion that higher mathematics would be quite out of place. He believes that the only way to get a thorough insight into any phenomenon is to obtain a clear 'mental picture' of what is taking place, and that, except to the mind of the trained mathematician, a mathematical solution too often fails to bridge over that wide gulf which separates the *abstract* from the *concrete*."

As before, line diagrams showing working principles have been used throughout, instead of the more usual

photographic views, which nearly always fail to bring out the essential features of a design.

Among the sections which may be mentioned as having been specially enlarged are those dealing with Constructional Details, Power Measurement, Induction Instruments, Current and Pressure Transformers, and Graphic Instruments. In connection with the latter it may be mentioned that the expression "grapher" or "graphic instrument" has been used throughout, in view of the confusion which arises from the use of the term "recording" when "integrating" is meant.

The symbols, direction of phase rotation, and nomenclature recommended by the International Electro-technical Commission and the British Engineering Standards Committee have been used as far as possible, and although at the time of going to press the revised Engineering Standards Committee's specifications for indicating instruments, graphers, and instrument transformers are not in print, there seems little doubt as to their provisions, which have been adhered to in the present volume.

The thanks of the author are especially due to Mr. L. Murphy for his valuable assistance in connection with various sections, and more particularly with those dealing with Potentiometers, Instrument Transformers, Induction Instruments, Wattmeters, and Power Factor Meters. Thanks are also due to Mr. G. Godfrey for his help in connection with the diagrams and illustrations.

Finally, the author feels that some apology is due, both to his readers and to the publishers, for the long delay which has occurred in the preparation of this edition, the first having now been out of print for some years, but he would plead as his excuse the special circumstances of the present time and the compensating advantage that he has, thereby, been enabled to include the latest developments.

KENELM EDGCUMBE.

May, 1918.

CONTENTS

CONTENTS

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

INDUSTRIAL ELECTRICAL MEASURING INSTRUMENTS

Introductory.

THE measurements which the electrical engineer is called upon to carry out consist, for the most part, of determinations of current, pressure or resistance, together with their derivatives, such as power, conductivity, power factor, frequency and so forth.

The instruments employed for this purpose fall naturally into the following classes :—

(1) Indicating.
(2) Recording or graphic.
(3) Integrating.

Of these the first two, alone, are dealt with in this volume.

In view of the confusion which often arises, it may be well to define these terms. **Indicating instruments** are those in which the quantity to be measured is read off a scale. In **recording or graphic instruments a** continuous record is obtained, usually on a paper chart. **Integrating meters** give the sum total of the product of the quantity, at any instant, into the time—for example, watt-hours[1] or ampere-hours. The watt-hour meter is, unfortunately, sometimes spoken of as a "recording watt-hour meter" or even as a "recording wattmeter," whereby considerable confusion is caused. For this reason the word "graphic" has been introduced and is used throughout this book.

[1] Mathematically expressed, a watt-hour meter gives the value of $\int VA\, dt$ where V and A are the instantaneous values of volts and amperes respectively.

A further subdivision of indicating instruments can be made into :—

(1) Deflectional pattern.
(2) Zero or "null method" pattern.

Symbols and Vector Rotation.

The **symbols** adopted throughout the present volume are those recommended by the International Electro-technical Commission,[1] and are as follows :—

Angles	α, β, γ, etc.
Power	P
Temperature Cent.	t
Frequency	f
Phase displacement	φ
E.M.F.	E
Current	I
Resistance	R
Capacity	C
Self-inductance	L
Magnetic flux	Φ
,, ,, density	B
,, field	H
Permeability	μ
Amperes	**A**
Volts	**V**
Ohms	Ω
Watts	**W**

Instantaneous values are shown by the corresponding small letters.

In the graphical representation of alternating phenomena an advance in **phase** is represented by a counter-clockwise **rotation.** For example, in the vector diagram of Fig. 144 the current I_1 is represented as lagging behind the pressure E_1, but the current I_3 leads as compared with the pressure E_3.

[1] See Publication No. 27 of International Electro-technical Commission (1914).

Errors and Accuracy.

In specifying that a measurement is to be made with a certain accuracy (or, more correctly, with a certain precision), care must be taken to distinguish between a number of distinct **sources of possible error** :—

(1) Inherent errors of the instruments used.
(2) Errors due to the method of measurement.
(3) Errors of observation.
(4) Mistakes on the part of the operator.

A simple measurement leading to many possible errors is, for example, the determination of the resistance of the shunt winding of a dynamo by means of a Wheatstone bridge. Taking them in order, the errors of the first class might be due to :—

(1) (*a*) Inaccuracy of the bridge.
(*b*) Want of sensitiveness of the galvanometer.
(*c*) Inaccuracy of the thermometer (assuming one to be used to measure the temperature of the field coil).

Under heading (2) would come :—

(2) (*d*) Effect of the resistance of the connecting leads and contacts.
(*e*) Difficulty of ensuring that the winding is at a uniform temperature, throughout.
(*f*) Even assuming this to be the case, there still remains the difficulty of determining that temperature.

Amongst errors of observation might be :—

(3) (*g*) Galvanometer not precisely at zero.
(*h*) Parallax in reading the thermometer.

The possibility of mistakes is almost unlimited; for example :—

(4) (*i*) Ratio plug might be in the wrong hole (so that perhaps the ratio is 10 : 100 when supposed to be 10 : 1,000).
(*j*) Resistances wrongly read off.
(*k*) Mistakes in working out the result.

Thus, apart altogether from the correctness of the instruments, we have enumerated at least eight possible sources of inaccuracy. It is not probable that they would all occur, and even if they did, the chances are that some would cancel others. The actual errors in practice might very probably amount to :—

Errors due to instruments	*a*, *b*	± 0·1 per cent.
	c	± 0·5° C.
Errors due to method .	*d*	negligible if care is taken.
	e, *f*	± 1° C.
Errors of observation .	*g*	negligible if care is taken.
	h	± 0·2° C.
Mistakes . . .	*i*, *j*, *k*	*nil* if care is taken.

Thus, the electrical errors come to 0·1 per cent. and the thermometer errors to 1·7° C. (or 0·65 per cent. for a copper coil), assuming, as is possible, that they are all in the same direction. Making, therefore, some allowance for *d, g, i, j,* and *k,* it is safe to say that such a measurement cannot be relied upon to within less than 1 per cent., and yet it is no uncommon thing to find the result given as, for example, "103·75 ohms at 15·5° C." The reading of the bridge was probably 10,375 ohms, and the ratio 10 : 1,000. If the galvanometer is sensitive, another figure may, perhaps, be estimated, and the result expressed as "103·758 ohms," or, if the observer were exceptionally conscientious, he would express it as "$103{\cdot}75_8$ ohms," thereby indicating that the last figure was only estimated, and could not absolutely be relied upon. Even if this last figure be neglected, the implied accuracy is 0·01 in 104, or say ·01 per cent., whereas the possible error has been shown to be about 1 per cent., or a hundred times as great.

It is of great importance that records of measurements

should not be given to more figures than can actually be vouched for, since, such a statement as "103·75 ohms at 15·5° C." implies that, at any rate, the experimenter was confident that the value lay between 103·7 and 103·8 ohms at 15·5° C., whereas, taking the above-mentioned errors into account, all that he is really confident of is that it lay between 103 and 104 ohms.

The value 103·758, or $103{\cdot}75_8$, claims what is known as "**six-figure accuracy,**" 103·7 "four-figure accuracy," and so forth. A result written as 12·000 claims five-figure accuracy, so that care should be taken not to write 12 as 12·0, unless the value is known to lie between 11·9 and 12·1. It is, however, usual to express accuracies (or, more correctly, errors) as percentages (*e.g.*, an error of 0·1 per cent.), or as one in so many thousands (*e.g.*, an error of 0·01 per cent. is an error of one in 10,000).

The precision aimed at in industrial work varies enormously. For example, in a house installation, if the insulation is known to lie between 1·5 and 2 megohms (that is to say, is estimated to within ± 15 per cent.) it will, as a rule, be quite sufficient, partly, it may be, because the required minimum has been well exceeded, but still more because the insulation resistance is known to depend so much on atmospheric conditions.

Apart from standard instruments, probably the highest accuracy in industrial work is demanded of central station voltmeters. Such accuracies as one volt in 500 are sometimes asked for, and at the same time it may be specified that the instrument is to be read at a distance. To comply with the latter requirement, a suppressed zero (see p. 146) is very probably demanded (a scale of 450 to 550 volts being perhaps called for). It is forgotten, in so doing, that whereas the observation errors are reduced, the electrical and mechanical errors of the instrument itself are actually increased, owing to creeping of springs, friction, risk of bending the pointer and so forth. Thus the two requirements are, to a large extent, antagonistic; and, taking all things into account, it is generally admitted that an accuracy of

$\pm$ 1 per cent. is all that is ever required of a switchboard instrument.

The case of instruments intended for standardisation purposes is different, since these must possess a greater accuracy than that of any instrument they are intended to check, and $\pm$ 0·3 per cent. of the maximum should certainly be the greatest inaccuracy allowed for a testing voltmeter intended for general standardising purposes.

Care must be taken to distinguish between **sensibility and accuracy,** which are by no means the same. For example, the sensibility of an instrument may be such that it can be read to 0·1 per cent., but its accuracy may be only 1·0 per cent. On the other hand, a less sensitive instrument, only capable of being read to 0·3 per cent, say, may have an accuracy of 0·5 per cent. The precision in the second case will be double that in the first, in spite of the lower sensitiveness.

The following table can be taken as indicating what is **to be expected of a good commercial instrument** of normal range used under normal conditions. The accuracy is expressed as a percentage of the reading at a point about three-quarters up the scale (see p. 9).

	Error. per cent.
Wheatstone bridge, highest grade	0·01
,, ,, P.O. pattern (up to 10,000 ohms)	0·1
,, ,, ,, ,, (above 10,000 ohms)	0·2
Deflectional ohmmeter	3·0
Potentiometer, highest grade	0·02
,, portable form	0·2
Moving coil voltmeter, laboratory pattern	0·25
,, ,, switchboard ,,	0·75
,, ammeter, laboratory ,,	0·5
,, ,, switchboard ,,	1·5
Moving iron voltmeter or ammeter, laboratory pattern (with a.c.)	0·5

	Error. per cent.
Moving iron voltmeter or ammeter, switchboard pattern (with a.c.)	1·5
,, voltmeter or ammeter, switchboard pattern (with c.c.)	2·0
Induction voltmeter, switchboard pattern	1·5
,, ammeter, ,, ,,	2·0
,, wattmeter, ,, ,,	2·0
Dynamometer voltmeter, laboratory pattern	0·5
,, ,, switchboard ,,	1·0
,, ammeter, laboratory pattern	0·75
,, ,, switchboard ,,	1·5
,, wattmeter, laboratory pattern	0·75
,, ,, switchboard pattern	1·5
Hot-wire voltmeter, switchboard pattern	1·5
,, ammeter, ,, ,,	2·5
Electrostatic voltmeter, 100 to 1,000 volts	0·75
,, ,, 1,000 to 8,000 ,,	1·5
,, ,, 8,000 to 15,000 ,,	2·5
Power factor meter, dynamometer type	2°
Graphic instruments, pen pattern, add to error of corresponding switchboard pattern	1·5
,, ,, inkless pattern, add to error of corresponding switchboard pattern	0·5
Electrical speed indicator (c.c. transmitter and movingcoil indicator)	1·5
,, ,, ,, (vibrating reed indicator)	0·5

From what was said when discussing the Wheatstone bridge test, it will be clear that the accuracy of the instrument itself is often quite swamped by experimental errors, and entirely erroneous conclusions arrived at. For example, it is no uncommon thing for an ammeter to be checked by placing it in series with an ampere-hour meter, although the temperature and other errors of the latter are possibly three times as great as those of the former. Or, again, a photometer

scale is read to half a millimetre, whereas the difference between consecutive readings on the same lamp very possibly exceeds a centimetre.

It is usual, when making a measurement, to take a number of observations and to find the **mean or average value.** In doing so it must be remembered that it is only certain of the variable errors that are "averaged out," and that any constant errors, due either to the instruments or to the method of measurement, will remain. It is, therefore, not necessarily safe to express the result to more figures than a single observation would warrant. A comparison of the individual observations with their mean, affords an indication of the consistency, although not of the correctness, of the results.

In some cases a single reading may be made more accurate than the mean of a number. For example, if it is wished to find the average potential difference at the terminals of a number of dry cells with a ten-volt voltmeter, one method would be to measure the potential difference of each cell and to take the mean. Owing, however, to the fact that the readings will be very low down on the scale (less than one-sixth of the range), the accuracy of measurement will be small. If, on the other hand, six cells were connected in series, the total voltage could be determined with considerable accuracy, and this value divided by six will give the required value for each cell. Even in so simple a case as this, however, there are several possible sources of error. In the first place, it will be noticed that the external resistance (that of the voltmeter) is the same whether there be one or six cells in circuit, so that the current flowing is widely different in the two cases. Again, it would be well, roughly, to test each individual cell, so as to eliminate any which gave abnormal readings. In expressing the result of such a test, the current flowing and the length of time the circuit had been closed before making the measurement should be stated.

It is often assumed that an **evenly divided scale** is the ideal to be aimed at, but, as a matter of fact, if the same percentage accuracy of reading is required at all points, the

divisions should be wider at the beginning than at the end of the scale. In a **logarithmic scale** (such as is shown in Fig. 1, which is similar to that of a slide rule) a given error of reading entails the same percentage error at all points. Very few instruments could, however, be given scales approaching this, exceptions being possibly dynamometer and hot-wire ammeters or voltmeters, moving iron instruments over part of their scales, and ohmmeters.

It is, therefore, unreasonable to expect the same **percentage accuracy at all points of the scale.** What might be called the "electrical errors" can safely be so expressed, but errors due to friction, observation, and so forth will be more or less constant, so that the precision

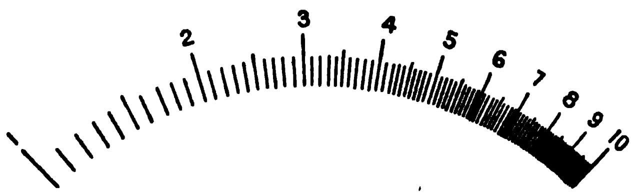


FIG. 1.—Logarithmic Scale.

should, strictly, be expressed in some such form as $\pm p$ per cent. $\pm q$. For this reason, it is now usual to guarantee instruments to be correct within a certain percentage of the maximum scale reading throughout or of the reading down to half-scale only, and of the maximum below this. For example, an ammeter scaled to fifty amperes and guaranteed accurate to within $\pm$ 1 per cent. of the maximum below half-scale, would be accurate to within half an ampere throughout. It would be absurd to expect it to be guaranteed to within 1 per cent. of the reading at, say, five amperes. The object in all cases is to express the accuracy in such a way as to take into account constant as well as proportional errors.

Care must be exercised when **multiplying or dividing** (and still more when squaring or cubing) a value which is only known to be accurate to a given number of figures. Take, for example, the case of a voltmeter having a scale

graduated up to 120 volts and provided with an additional resistance for 600 volts. Suppose the reading to be 106, this may very probably be known to be correct to three figures, that is to say, the true reading is known to lie between 105·5 and 106·5. After multiplying by five, however, the value 530 will not be correct to three figures, since the actual volts may be anything between 527·5 and 532·5. For this reason it is much more satisfactory to speak of a result as being correct to within so much per cent., rather than as correct to so many figures, since the percentage accuracy is not changed by multiplying or dividing.

The case of **squaring** or raising to any power is different. For example, if a measurement is accurate to within 2 per

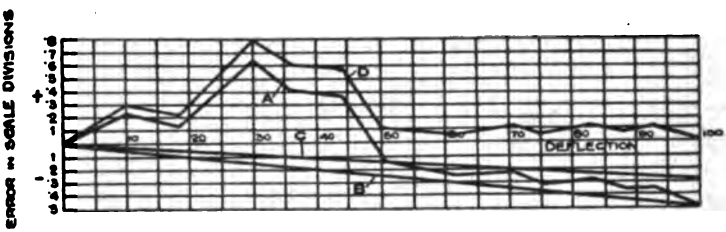


FIG. 2.—Scale Error Curves.

cent., and the value is squared, the result can only be relied upon to within 4 per cent.; if it is cubed, to within 6 per cent.; or if raised to the nth power, to within $2n$ per cent. As showing how important this sometimes becomes the case of photometers may be instanced. The candle-power of a metallic filament lamp varies, usually, as about the fourth power of the voltage, so that if the voltage is only known to within 1 per cent. the candle-power cannot be relied upon to within less than 4 per cent.

In the case of many instruments, notably those intended for use with alternating currents, the torque is proportional to the square of the quantity measured, whilst the scale is graduated directly in terms of the latter. In such a case the reading is proportional to $\sqrt{\text{torque}}$, and a change of reading amounting to n per cent. is produced by a change of torque of $2n$ per cent. (see also p. 169).

In the case of a deflectional instrument it is often useful to **distinguish between the errors** as (1) scale errors, which can be determined once and for all, (2) errors which follow a known law (*e.g.*, temperature errors), and (3) other errors which can only be determined empirically from time to time. These three classes of error are separated in Fig. 2, where the ordinates represent errors, expressed in scale divisions, and the abscissæ deflections in scale divisions. Curve A gives the total error, points above the horizontal line indicating that the instrument reads high, and *vice versâ*. At the top of the scale the reading is found to be 0·5 divisions low. The straight line B, drawn through this point and the zero, represents the curve of errors which the instrument would have if the scale were correctly drawn.

From this it follows that the scale error, assuming the zero and top scale points to be correct, is represented by the difference between curve A and the straight line B. This difference is plotted in curve D; and, having once been determined, it only remains so to adjust the instrument as to be correct at the top of the scale, and the necessary correction, read off curve D, can be applied at all other points. It may not be possible to set the instrument so as to be correct at the top point, but this is unnecessary, so long as the error at this point is known. Suppose it to be 0·3 divisions; then the straight line C drawn through this point forms the datum line to which the scale error corrections have to be added. The same reasoning applies to corrections for temperature and any other errors which can be expressed as a percentage of the reading. The procedure is (1) to apply this percentage correction, and (2) to add or subtract the scale error as taken from curve D.

When an instrument is said to read x per cent. low at a given point, there still remains the question of **how this correction is to be applied,** that is, whether—

$$\text{True value} = \text{Reading}\left(1 + \frac{x}{100}\right)$$

or—

$$\text{Reading} = \text{True value}\left(1 - \frac{x}{100}\right).$$

The former conception is the one usually adopted in this country, and has the advantage of being much easier to apply. It is clear that, so long as x is small, the difference between the two conventions is negligible.

It may be added that when the correction is given as $+x$ it is usually understood to mean that the correction (x) is to be *added* to the instrument reading in order to obtain the true value, and *vice versâ*.

Besides the **sources of error** dealt with elsewhere, the following may be alluded to here. One of the commonest lies in a certain amount of **stickiness, due to friction** (see also p. 36). As this is always present to a greater or less degree, it is well to tap the case gently before taking a reading. If the friction is excessive it is, probably, due either to the jewels having been damaged or screwed down too tightly, or else to some mechanical obstruction, such as a hair, or, in the case of a permanent magnet instrument, an iron filing. The latter is best removed by means of a thin strip of iron or steel passed through the air gap. A filing will usually adhere to this and can be withdrawn.

In the case of instruments with horizontal axes, a **want of balance** is often found, and, whether the instrument be controlled by a spring or by gravity, inaccuracy is sure to result. Such want of balance may be due to a fall, a heavy overload, or to deformation of the pointer owing to changes of temperature, or even to stresses in the material of which it is made. Edgewise and other instruments with long pointers are particularly liable to this trouble.

A very common and often-unsuspected source of error lies in a **stray magnetic field.** Nearly all instruments are susceptible to this (the electrostatic and hot wire types being exceptions), and the weaker the working field of the instrument, the more liable it is to suffer. For this reason dynamometer instruments are the most susceptible, after which comes the moving iron pattern, while the permanent magnet moving coil and the induction types, with their strong fields are almost immune.

The disturbing fields may be :—

(1) The earth's field.

(2) That due to a permanent magnet or a continuous current electro-magnet.

(3) That due to an alternating current electro-magnet.

(4) That due to a conductor carrying continuous current.

(5) That due to a conductor carrying alternating current.

Alternating current instruments are unaffected by (1), (2), and (4), while continuous current instruments are unaffected by (3) and (5).

Causes (4) and (5) are the most serious in modern practice. The field strength at a distance l from an infinitely long straight conductor, carrying a current I, is proportional to—

$$\frac{I}{l}.$$

If the length of the straight conductor is not infinite, but is $4l$, $5l$, or $10l$, the field strengths will be only 3 per cent., 2 per cent., and $\frac{1}{2}$ per cent. smaller, respectively, than those given by the formula. For all practical purposes, therefore, it may be said that the disturbing effect is directly proportional to the current flowing and inversely proportional to the distance of the conductor from the instrument. In practice the return is usually somewhere near, and has a neutralising effect, so that the disturbance is reduced. For example, if the return conductor is at a distance of $2l$ from the instrument the error will be halved.

One maker gives the following minimum distances for a conductor, from a moving iron instrument in cast-iron case, if the inaccuracy is not to exceed $\pm$ 1 per cent. :—

Current in amperes . .	100	200	300	400	500	1,000	2,000
Minimum distance in centimetres	8	15	20	25	30	50	80

In the case of a moving coil or induction instrument these distances could probably be reduced to one quarter, while

for a wattmeter or other dynamometer type they should be doubled. If the return conductor is near the other, all distances might safely be halved.

Three methods are available for **eliminating such errors** :—

(1) Turning the instrument through 180° and taking the mean of the two readings.

(2) Shielding it by a soft iron screen or even by a cast-iron case.

(3) Making the movement astatic.

Method (1) is laborious, and is at best only applicable to portable instruments. Method (2) is effective in the case of moving coil and moving iron instruments, and to a smaller extent, and with special precautions, in the case of dynamometer instruments (see p. 177). Method (3) is by far the best, but has the disadvantage of rendering the moving system heavy and of increasing the power expended (see p. 86). It must also be borne in mind that magnetic fields are seldom uniform, and the two opposed windings are necessarily a certain distance apart. The success of the method depends upon their both being subjected to identical fields. In order to avoid disturbance testing instruments should be kept well away from one another, particularly if they are of a type susceptible to stray fields.

In the case of moving coil, induction and, to a lesser extent, moving iron instruments,[1] the percentage error due to a given stray field will be appreciably the same at all points of the scale. In a dynamometer instrument, however, it will vary with the relative position of the moving coil (see also p. 181).

An insiduous source of trouble lies in the accidental use of **magnetic materials.** Thus apart from nickel which is magnetic, brass and, more rarely, aluminium may contain an appreciable quantity of iron, and balance weights or formers made of, or even plated with, such materials will produce most unexpected results.

Errors due to **thermo-E.M.F.'s** are dealt with more fully

[1] In the case of a moving iron instrument of the repulsion type (*e.g.* Fig. 72) the error is not proportional, but is represented by an almost constant deflection at all parts of the scale.

on pp. 46—49 and 121. They only occur in connection with continuous current tests, and can be neglected in all measurements above, say, ten volts.

Disturbance occasionally arises through **electrostatic effects.** One of the commonest sources of this trouble lies in the accumulation of a charge on the glass front of an instrument, thereby attracting the pointer. This charge can be dispelled by breathing upon or damping the glass front, and so allowing the charge to leak away to the case. Electrostatic instruments (see p. 187) are the most susceptible, and the glass front, if extensive, should be provided with a conducting grid of gold leaf applied to the inner face of the glass. A conducting varnish consisting of sulphuric acid and gelatine has been used for the same purpose, but is unsatisfactory in that it leads to corrosion of the working parts.

Electrostatic disturbances are also liable to occur if two parts of an instrument are connected to circuits at different potentials. This occurs, for example, when an instrument winding is connected to a high-tension circuit, and the case is earthed (*e.g.*, on the Thury high-tension continuous current system), or in a dynamometer wattmeter of which the series and pressure coils have currents in them, derived from different sources. The remedy in the latter case is to join the two windings together at one point, and in the former to connect the case to the winding.

Temperature Errors.—These are dealt with more fully under the respective instrument types. It may be mentioned here that, besides errors due to a change in resistance of the windings (the resistance increasing by about 0·4 per cent. per degree Centigrade rise, in the case of copper), control springs will decrease in strength with rise of temperature (about 0·04 per cent. per degree Centigrade), and a permanent magnet will give a weaker field as the temperature rises (usually about 0·02 per cent. per degree Centigrade). The permeability of iron decreases with rise of temperature by about the same amount as the strength of a spring, so that the two effects largely counterbalance one another.

Constructional Details.

Cases.

The form of case to be used depends chiefly upon the space available and the conditions under which the instrument is to be employed. The more usual patterns are :—

(1) Portable wooden cases.
(2) Round switchboard cases.
(3) Sector-shaped cases.
(4) Edgewise cases.
(5) Special round, sector, square, or other shaped cases for direct attachment to switchgear.

Portable cases when likely to be subjected to rough usage are best made of oak or teak and provided with flaps arranged to protect the glass. The modern practice is to make the case form part of the instrument, rather than to slip the latter into a case from which it has to be removed each time it is used.

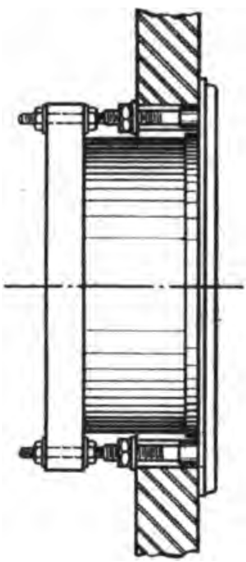


Fig. 3.—Flush Type Instrument.

Round switchboard instruments are sometimes supplied up to 12 ins. or more in diameter, but, except for special purposes, it is preferable to restrict their use to scale lengths of about 7 ins. and, if longer scales are required, to employ the **sector pattern,** which is much more economical of space. For example, a round instrument having a 9-in. scale would occupy a width of about 14 ins., whereas a 9-in. scale sector instrument would be only some 11 ins. wide. For this reason the practice of designating an instrument by the size of the case is to be deprecated, and the length of the scale should always be given.

Edgewise instruments are useful when the space on the board is restricted, as is often the case on feeder panels.

They are not, however, very satisfactory when great accuracy is demanded, owing to parallax errors. For this reason the angle subtended by the scale should not exceed say 70°.

Recently, an edgewise instrument has been developed in Germany in which the scale is flat instead of curved, the **pointer being caused to travel in a straight line** by means of a link motion, such as that described on p. 361. The

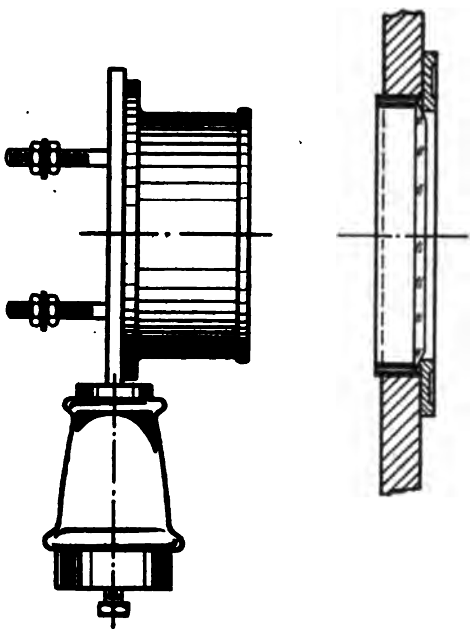


FIG. 4.—High-tension Ammeter.

extra friction and "back-lash" introduced, however, are such as to detract greatly from any possible advantage.

In another variation of the edgewise pattern, the curved scale is split and so shaped as to present the apex of a V to an observer standing in front of the instrument. The pointer "flag" is of V shape, as is also the glazed front of the case. The advantage of this arrangement is that the scale can be clearly seen from the side, instead of only from directly in front, as is the case with the ordinary type.

Round, edgewise, and even sector instruments are occasionally arranged for **flush mounting,** particularly on the Continent. Fig. 3 shows in section the mounting of such an instrument of the round pattern. The flush arrangement is neat in appearance, but the cutting of the slate or marble panel is expensive and in this country has not been received with much favour.

High-tension instruments, with which it is either not possible (*e.g.*, for continuous current) or undesirable (*e.g.*, on

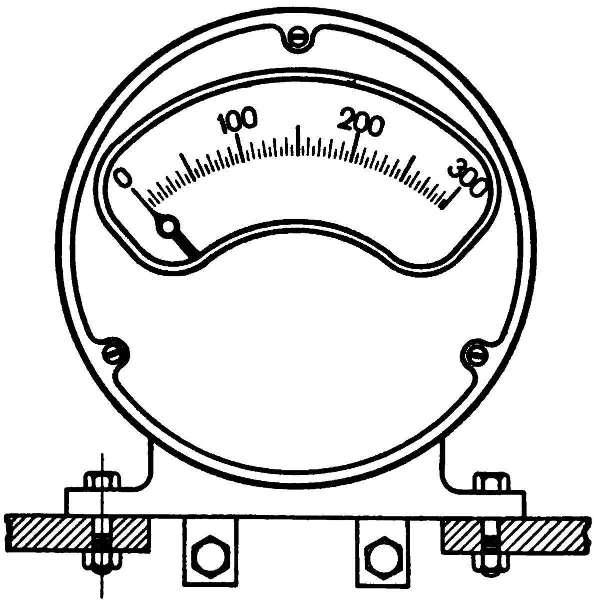


FIG. 5.—" Controller " Pattern Ammeter.

the score of expense) to employ transformers (p. 312), are sometimes mounted on insulators behind the switchboard in which a glazed opening is cut (see Fig. 4).

Another arrangement consists in a glass cover, either moulded or built up, which completely encloses the instrument, or, again, an earthed metal cage may be put over the whole panel. In any event, it is essential that the metal instrument case should be connected to the winding at one

point in all high-tension systems, otherwise disturbances due to electrostatic influences will arise (see also p. 15). Another alternative is to employ a case constructed throughout of insulating material. If this is done, care must be taken that no exposed metal parts, such as screws, etc., pass through the case. On the other hand, it is always preferable to keep

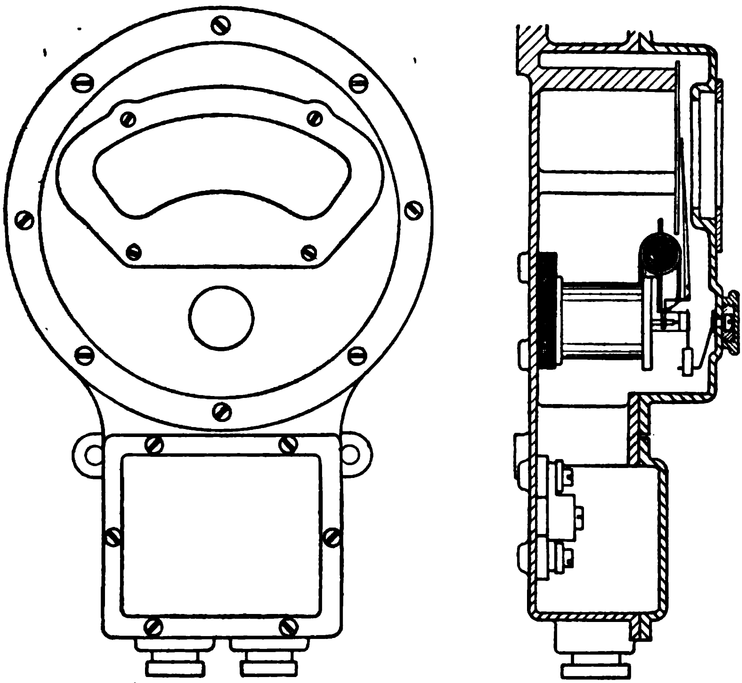


FIG. 6.—Watertight Instrument.

the high-tension current away from the instrument by the use of a transformer and to earth the metal case. The lead connecting the case to the main earthing cable of the station should not be more than about five yards in length or smaller than the equivalent of No. 8 s.w.g.

For special purposes, several types of case have been developed during the last few years, particularly in connec-

tion with enclosed switchgear, for factory and mining work and also for use on board ship. Fig. 5 shows what is known as the "**controller**" pattern, and Fig. 6 a "**watertight**" instrument with terminal box and glands.

For marine work, a prolonged test of water-tightness either under a definite head of water or a definite internal pressure is often called for, and protection against rough usage on shipboard is afforded by the use of "wired" glass, although this latter somewhat obscures the scale. For use in fiery mines a "**flame-proof**" instrument has been designed, similar to that shown in Fig. 5 or Fig. 6, but having a deep flange with carefully machined joints. It would appear to be better practice, however, to enclose the whole instrument in a flame-proof switch-box rather than to attempt to render the instrument itself proof. In this connection it may be pointed out that it is, in any case, futile to attempt to make an instrument or switch-box "gas-tight," as is sometimes suggested. In the long run, gas will find its way in, and therefore all that can be done is to prevent the flame passing out in the event of an explosion taking place inside.

Some years ago it was the custom to specify open-fronted brass-cased instruments for all high-class work, but it is now realised that **iron cases finished in black and nickel** or black and copper are far more durable and, moreover, protect the instruments both mechanically and magnetically (see p. 13).

The usual finish is a bright, hard, black stove enamel, but some engineers prefer a matt surface, as being less liable to reflect the light and so distract the eye when taking a reading. For naval use, **gun-metal,** usually painted white, blue, or red, is much used for cases exposed to sea water.

Whatever form of case is adopted, it is essential that the **opening in the front** should be large enough to expose a liberal expanse of the dial. This is particularly important when instruments are erected at some distance above the level of the observer's eye.

Scales[1].

Sufficient attention is not always directed to the marking of the scale or the shape of the pointer. Silvered brass, **engraved scales** were at one time asked for, but, as may be imagined, it is not easy to obtain any great accuracy by this means, since the divisions have first to be marked off by hand and afterwards cut on an engraving machine. **Enamelled metal scales** with painted divisions have much the same disadvantages, added to which the enamel is liable to crack and even to flake off after a time, especially in hot climates. It is now fully recognised that, all things considered, a scale carefully drawn out on good surface card, mounted on metal, is the most satisfactory, and if properly fixed[2] should show no tendency either to peel off or to discolour. At the same time, metal scales are still used to some extent for **tropical** work.

In **calibrating** an instrument, a very usual procedure is as follows. Readings are first taken on a scale divided into degrees. A curve is plotted connecting, say, amperes and the corresponding deflection on this scale. From the curve the actual scale is drawn, in Indian ink, by means of a special scale-drawing mechanism. For standard instruments it is preferable to mark the actual points corresponding to some ten or fifteen current values and then to interpolate the intermediate divisions.

In this way the highest possible precision is attainable, and a scale accuracy of 0·1 division on a 100 or 150 division scale is usually claimed. The value of the smallest division on the finished scale should be 1, 2, or 5 or some decimal multiple or sub-multiple of these, such as 0·001, 50, and so forth.

The **form of figure** used is of importance in order to ensure maximum legibility. Trotter has given considerable attention to this question, and some of the figures proposed[3]

[1] See also p. 16.
[2] When extreme heat, and still more excessive dampness, is to be expected, the card scales should be riveted or otherwise mechanically held in place.
[3] *Journal Inst. E.E.*, Vol. 54, p. 273 (1916).

by him are shown in Fig. 7 (upper set). Of the various line thicknesses there illustrated that of the "3" is probably the best. Fig. 7 (lower set) shows the figures adopted by the Admiralty for naval instruments. They will be seen to be very similar to those of Trotter, but have the advantage of occupying slightly less lateral space, which is sometimes of importance.

Without overcrowding, it is often difficult to insert as many numbered points as is otherwise desirable, particularly when the maximum scale reading is high, *e.g.*, 12,000 volts. In

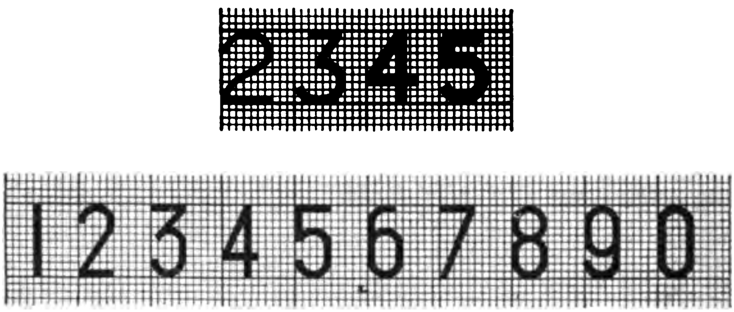


FIG. 7.—Scale Figuring.

such cases, it is often possible to print the figures radially, instead of tangentially, or the last two or three zeros can be printed above (*e.g.*, 12^{000} or 5^{00}).

For laboratory use, instruments should have finely divided scales (though divisions of less than say 0·5 mm. or 0·5° are not to be recommended), and the pointers should be bent up on edge so as to present a fine line to the eye. Under the scale should be fixed a mirror, to avoid parallax. This is usually of silvered glass, though occasionally polished metal is employed. Various refinements have been put forward, such as stretched silk threads as pointers, travelling mirrors or magnifying lenses, and so forth, but such adjuncts are, usually, quite unnecessary.

In the case of standard instruments the **numbering** should be small and at short intervals, and where several

ranges are to be read on the same scale it is convenient to indicate the values of the main divisions for each range. When the scales for the various ranges follow precisely the same law this is preferable to printing two or more distinct sets of divisions. For this reason the ranges chosen should form convenient multiples of one another, for example, 1, 10, 100, or 1, 5, 25, etc. In the case of instruments having evenly divided scales, each range can conveniently be made one-tenth of the next higher, unless extreme accuracy is required, when one-fifth is preferable. For scales which are cramped at the lower end, such as moving iron, dynamometer, induction or hot-wire instruments, less than one-fifth is inadmissible.

For switchboard instruments, which have, as a rule, to be seen from a distance, and often in a bad light, finely divided scales are not only unnecessary, but misleading. Bold divisions, ranging from $\frac{1}{16}$ in. to as much as $\frac{1}{2}$ in. apart (or say not less than 1°), should be insisted upon. By making the thickness of the main divisions greater than that of the rest clearness is sometimes increased, but this is only admissible in the case of switchboard instruments. The pointer, also, must be broad throughout its length, and be provided with a spear-shaped end, terminating in a fine point, by means of which accurate readings can be taken when it is possible to observe the instrument from close by. The tip of the pointer should come close to the scale to avoid parallax errors.

For central station work, where the light is often not of the best, **illuminated dials** are convenient. Such instruments are usually of the sector shape, although occasionally edgewise or even round instruments are so arranged. The scales are usually painted upon semi-transparent opal glass. Some makers use opaque scales and illuminate them from the front by means of a concealed lamp, but the transparent scale is to be preferred.

For various purposes, a demand has arisen for **self-luminous scales** which can be seen in the dark. Messrs. Paterson, Walsh, and Higgins, of the National Physical

Laboratory, who have given considerable attention to the construction of such scales for compasses and other instruments, recommend[1] the following procedure :—

The luminous powder, consisting of zinc sulphide with about 0·03 per cent. of radium bromide, is mixed with the minimum possible quantity of varnish or other binding material, and is applied to the scale by means of a brush. The thickness of the lines forming the figures, etc., should be about one-sixth of their length, and the illumination

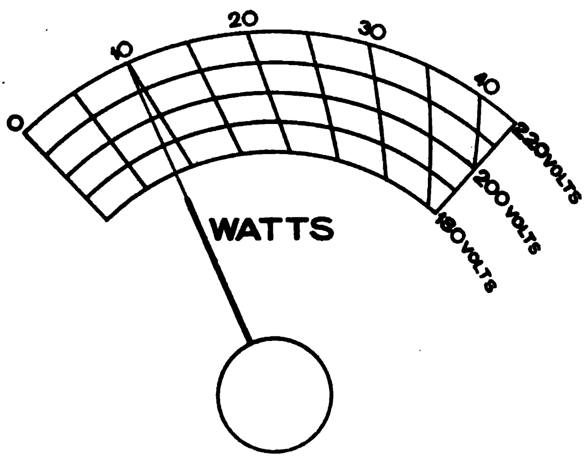


FIG 8.—Ammeter scaled in Watts.

will correspond to a surface brightness of about 0·02 foot-candles. This luminosity falls off during the first year by about 50 per cent., after which it remains fairly constant.

Certain instruments, the induction pattern for example, lend themselves particularly well to a circular scale (often known as a "**disc**" **scale**) subtending about 300°. In fact, as is shown when dealing with such instruments (p. 175), it is actually easier to produce a disc scale induction instrument than one having a 90° scale, and few of the latter pattern are now made. With a view to obtaining uniformity on a

[1] "An Investigation of a Radium Luminous Compound," by C. C. Paterson, J. W. T. Walsh, and W. F. Higgins (*Proceedings of the Physcial Society of London*, Vol. 29, p. 215 (1917)).

board on which both alternating and continuous current instruments are mounted, moving coil disc instruments have been developed (see p. 153), although the moving coil principle does not lend itself nearly so well to this purpose.

In the case of disc scale instruments, two alternative **methods of figuring** can be adopted. In one, the figures radiate from the centre, the tops being always turned away

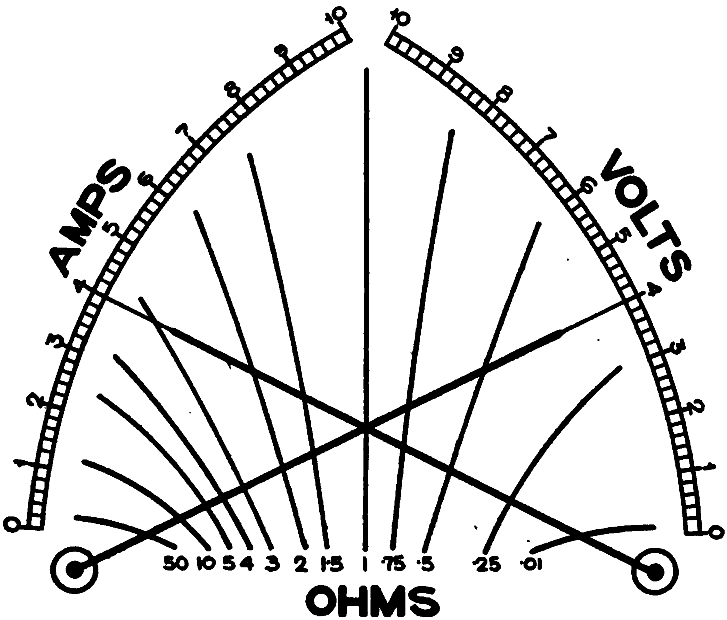


FIG. 9.—Volt-Ammeter with Ohm Scale.

from it, as in the ordinary clock dial ; in the other all the figures are arranged vertically (see Fig. 141). Again, the figures may be placed outside the scale divisions, but are better inside them, as giving a longer scale with the same size of case.

Fig. 8 shows a form of scale which is useful for some purposes. The particular instrument illustrated is an ammeter, so graduated as **to read watts at any voltage** between 180 and 220. In the illustration, if the voltage was 220 the

consumption would be 10 watts; at 200 volts it would be about 9 watts, and so on. A similar form of scale has been used to allow for the cold junction temperature in thermo-electric pyrometers (see p. 298), the concentric lines being then marked with cold junction temperatures.

Fig. 9 shows a special scale which has been developed for those cases in which the **ratio of two quantities** is to be determined. It has been applied to ohmmeters, power-factor meters, frequency meters, and mains insulation testers, amongst others. The actual scale shown in Fig. 9 is that of an ohmmeter. One pointer indicates current (4 amperes), the other pressure (4 volts), while the point at which they cross gives the ratio of the two, that is, the resistance (1 ohm). Such scales are not capable of any great accuracy and are but little used.

Insulation.

The problem of insulating the winding from the case is an important and at the same time a difficult one. The best modern practice demands that the case shall be of metal **efficiently earthed,** so that, even if the insulation of the winding breaks down, no danger can be incurred by touching the case.

An exception as regards earthing is made in the case of electrostatic voltmeters for pressures of 3,000 volts and over, which are, as a rule, fixed high up on the board, and are often fitted in **insulating cases,** protected by fuses and high resistances (see p. 196). Since the movement is alive (unless condensers are used, see p. 190), the case, if of metal, has to be made very large to preclude sparking across.

The insulation of instruments intended for use in **hot and damp climates** is a matter requiring great care. Mica or micanite should be used whenever possible. Press-board (presspahn) and fibre are to be avoided, as they are hygroscopic and become distorted with damp. The case should be made as airtight as possible, and the packing used for the purpose must be insect-proof.

A source of weakness in the insulation of many instruments lies in the **pointer.** Flexible metal stops are essential to limit its travel, and unless these are insulated with the greatest care they are liable to put the pointer to "earth" in the event of a heavy overload forcing it against them. For this reason, the pointer itself should always be carefully insulated from the live parts of the instrument. This applies with even greater force to the **pen arms** of graphic instruments (see p. 340), since they are liable to be handled while alive.

Every instrument should have a **test pressure** applied for one minute much greater than that at which it will be worked. Low-tension instruments are best tested to 2,000 volts, and high-tension instruments to twice the working pressure plus 1,000 volts. Excessive pressure tests for low-tension instruments are not only unnecessary, but actually harmful, since the insulation is thereby needlessly strained and may even be permanently damaged.[1] In the case of instruments worked off transformers the test applies to the insulation between the primary of the transformer and its secondary or core, the instrument itself being tested to 2,000 volts. The British Standardisation Rules lay down a pressure test of four times the pressure to earth plus 2,000 volts for both current and pressure transformers. The breakdown pressure is more important than the value of the insulation, but this latter should not be less than 10 megohms to earth, or 5 megohms between the current and pressure windings of wattmeters and power-factor meters.

Control.

The controlling force in modern instruments is almost always exerted either by gravity or by a spring. In the cheaper instruments of the moving iron pattern **gravity control** is employed, but for switchboard use spring control is much to be preferred, owing to the difficulty which is

[1] This is particularly the case if the test pressure is long applied. For some test figures bearing upon this point see *Faraday House Journal*, 1917, p. 71.

experienced in setting a number of instruments absolutely level. Fig. 10 shows a typical arrangement of controlling and balancing weights in a "gravity" instrument. In the position shown, the pointer P would be at the zero point of the scale, and the full deflection would take it to P′, the angle ϕ being, as a rule, 80° to 90°. The moving iron at C is balanced by P and B, or, if there is any resultant, it should be in line with the weight A (*i.e.*, vertically up or down), so that any adjustment of A will not alter the zero

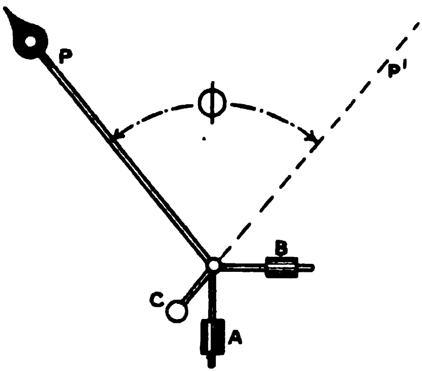


FIG. 10.—Balance and Control Weights.

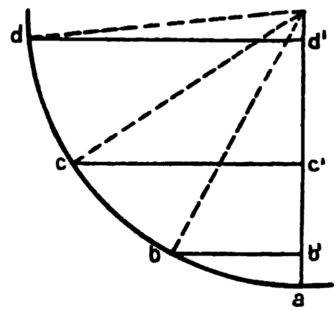


FIG. 11.—Gravity Control.

position, but will proportionately affect the torque at all points on the scale.

As the pointer is deflected, the weight takes up successive positions, such as *a*, *b*, *c*, and *d* in Fig. 11, the torque at each point being equal to the weight multiplied, respectively, by zero, $b\,b^1$, $c\,c^1$, and $d\,d^1$. It will be noticed that the control increases more rapidly at first than towards the end of the travel. The torque is, in fact, proportional to the sine of the angle of deflection. In the case of a **spring control**, on the other hand, the torque is nearly proportional to the angle of deflection. This difference is shown in Fig. 12, in which the ordinates represent torque and the abscissæ angular deflections. Curve II. shows the connection between torque and deflection in the case of a gravity control, and Curve I. of a spring control. The torque at the end of the

travel (80° to 90° deflection) is the same in each case, but the weight exerts a greater torque at all other points. The effect on the form of scale is quite appreciable, and a moving iron instrument, for example, gives a more open scale at the lower end when spring-controlled than when gravity-controlled.

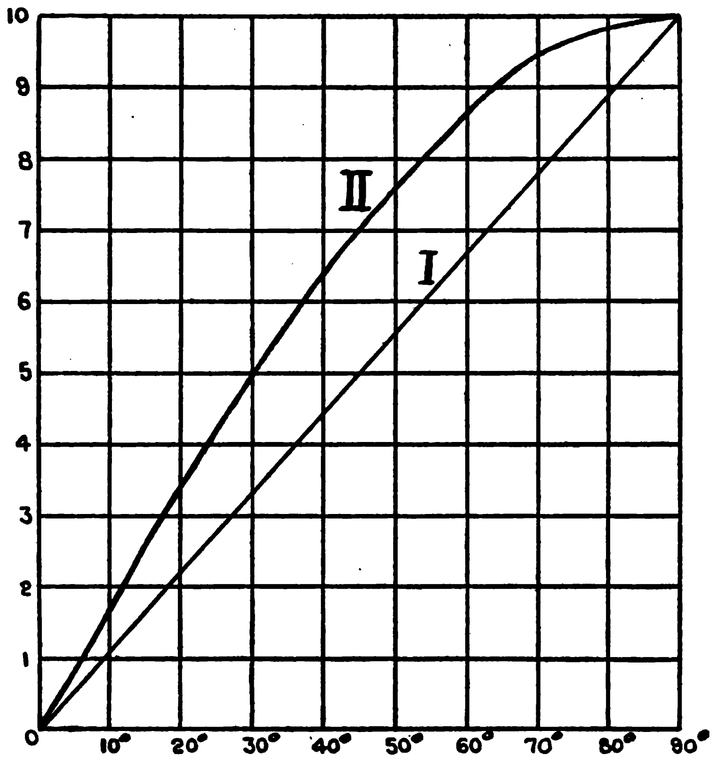


FIG. 12.—Spring and Gravity Control compared.

It should be remembered, in connection with controlling or balancing weights, that if w is the weight and r the distance from the centre, then :—

Maximum torque is proportional to $w\,r$.
Weight on pivots is proportional to w.
Momentum is proportional to $w\,r^2$.

Hence for a given torque we have :—

Weight on pivots proportional to $\frac{1}{r}$

Momentum proportional to r.

Thus it follows that, as far as friction is concerned, the weight should be at the end of a fairly long arm, but considerations of damping prevent this being carried too far.

The design of **control springs** demands very great care if permanent accuracy is aimed at. It is well known that if any material is bent or twisted beyond a certain limit it will take a permanent or sub-permanent "set" after the bending force has been removed. This shows itself in measuring instruments by a failure to return to zero[1] after prolonged deflection. Readjusting to zero does not get over the difficulty, since, after standing for some time, the spring will probably regain its normal shape, and the trouble will reappear as soon as the current is switched on.

Taking the case of the ordinary phosphor-bronze spiral spring, such as is used in measuring instruments, there is for a given length of spring and a given angular deflection (say 90°) a maximum thickness which it is unsafe to exceed. If greater strength is required the width must be increased. The torque exerted by such a spring is given by the formula :

$$T = \frac{E\, b\, t^3 \theta}{\cdot 6875\, l},$$

where T is the torque in centimetre grammes, t the thickness, b the breadth, and l the length of the spring, all in centimetres ; θ is the angle in degrees through which the free end is deflected (say 90°) ; E is what is known as the "modulus of elasticity" (in kilogrammes per square centimetre), and is a constant depending upon the material. For phosphor-bronze, such as is usually employed for springs, E may be taken as 1,150,000.

When such a spring is bent, the material along what may be called the "neutral axis" is unstrained, while that outside it is extended and that inside it is compressed. The

[1] This "zero error" must not be confused with the effect of a thermo-E.M.F. (see p. 14).

thicker the material the greater are these forces. The stress is, in fact, equal to $\frac{6\,T}{b\,t^2}$ grammes per square centimetre, and it is found from experience that this quantity must not exceed about 600 kgs. per square centimetre for phosphor-bronze, if a permanent or semi-permanent set is to be avoided.

Assuming a deflection of 90°, it can be shown by combining the two formulæ just given that the length of a spring must be at least 1,500 times its thickness. In the case of suppressed zero and disc scale (p. 24) instruments the angular deflection will be greatly in excess of 90°, and the difficulty of obtaining sufficient torque, without exceeding the allowable ratio of length to thickness, becomes greater. For example, a scale reading from 500 to 600 volts entails a spring set-up through 540° at its maximum deflection (assuming a 90° scale), so that the length must be $1{,}500 \times \frac{540}{90}$, or 9,000 times the thickness—an almost impossible proportion.

Again, a spring for a moving iron voltmeter might have the following dimensions :—

$$t = \cdot 006\,\text{in.}; \; b = \cdot 03\,\text{in.}; \; l = 15\,\text{ins.}$$

Hence $$\frac{l}{t} = 2{,}500.$$

Such a spring would serve perfectly well for a free zero instrument, but would be quite unsuitable for the 500 to 600 volt range. In fact, the maximum permissible set-up with this spring would be 240 to 600 volts, for example.

As another example may be cited a spring suitable for a moving coil instrument. An actual spring had the following dimensions :—

$$t = 0{\cdot}0058\,\text{cm.}; \; b = 0{\cdot}18\,\text{cm.}; \; l = 28{\cdot}5\,\text{cms.}$$

In this case $\frac{l}{t} = 5{,}000$ nearly. The torque of this spring, which was wound in eight turns, was 0·2 cm.-gm.

It is usually assumed that the torque exerted by a spring

is proportional to the deflection (**Hooke's law**), but this is not strictly true in practice, small variations being always found in even the most carefully made springs. Such discrepancies are of no great importance, however, as they can be allowed for in calibration.

The strength of a spring, *i.e.*, the torque exerted per degree of deflection, **can be measured** in two ways. The simplest is to attach the spring to a lightly pivoted horizontal spindle carrying a carefully counterbalanced pointer. The position of rest of the pointer, with the spring undeflected, is observed, and a known weight (g grammes) hung on the pointer at a given distance (r cm.) from the centre. The angle (a) through which the free end of the spring has to be turned to bring the pointer back to its former position is then noted. The strength of the spring in centimetre-grammes per degree is $\frac{gr}{a}$.

Another, though less convenient, method is to attach the spring to a very finely pivoted flywheel; one of about the weight of a penny being very satisfactory for a small spring. The time occupied in making ten swings is noted, and this time is inversely proportional to the square root of the strength of the spring. In fact, under these conditions—

$$\text{Torque} = \frac{4\,\pi^2 I}{T \times 981},$$

where the torque is expressed in centimetre-grammes per radian (57·3°); I is the moment of inertia in C.G.S. units, and T the time of one complete period in seconds.

Some makers employ two springs wound in opposite directions with a view to eliminating any **error due to expansion** or contraction with change of temperature. The error is, however, quite negligible, and many therefore employ one spring only, leading the current into the moving system, when required, by means of silver or copper ligaments exerting the smallest torque possible. It is impossible altogether to eliminate the control exerted by such ligaments, so that for the most accurate work it is preferable to lead the

current into and out of the moving system by means of the springs. Phosphor-bronze springs, moreover, have a tendency to uncoil themselves as time goes on, and this effect is eliminated if two springs, wound in opposite directions, are used.

An advantage of ligaments is that their **resistance**[1] is considerably less than that of phosphor-bronze springs. In the case of voltmeters this is of little importance, but for moving coil or dynamometer ammeters it is essential that the resistance of the circuit should be small, since, added to that of the coil, it forms a determining factor in the matter of temperature error. As has been seen, the controlling torque is proportional to $\frac{bt^3}{l}$; but the conductivity is proportional to $\frac{bt}{l}$. Hence it follows that for a given torque, the thinner the spring, the lower will be its resistance, a ratio of 15 : 1, for breadth to thickness, being suitable.

In order to increase the conductivity of springs, alloys of silver and copper have been tried, but are all more or less liable to deformation, unless selected with the greatest care. The resistance of phosphor-bronze may be taken as about ten times that of copper, and that of a high conductivity bronze as about twice that of copper. The resistance of the last spring cited above ($0{\cdot}18 \times 0{\cdot}0058$) in high conductivity phosphor-bronze would be about 0·067 ohm. Another spring giving the same torque (0·2 cm.-gm.), and having $b = 0{\cdot}12$, $t = 0{\cdot}0071$, $l = 35$ cms., had a resistance of 0·1 ohm, or some 50 per cent. higher.

Both the resistance and the torque vary with temperature. The resistance **temperature coefficient** varies slightly with the material, but may be taken as about 0·2 per cent. per degree Centigrade, the resistance increasing with a rise of temperature. The torque, on the other hand, decreases to the extent of about 0·04 per cent. per degree Centigrade rise of temperature.

The controlling spring is attached to a **zero-setting**

[1] See also p. 73.

lever, which should be accessible from outside the case. In switchboard patterns it is preferably protected by a cap or plate, removable by means of a screwdriver, to prevent unauthorised interference. It must be borne in mind that the resetting to zero of a pointer which has left it requires care, since, if it is due to the bending of the pointer or to any cause other than a slight deformation of the springs, inaccuracy will result.

Pivots and Jewels.

Of all the mechanical parts of an instrument the most important and, at the same time, the most liable to derangement are the pivots. Various devices have been tried such as friction wheels, knife edges, needle points working in hardened cups, and suspending ligaments, but, with the exception of the last two, all have been abandoned in favour of steel points in sapphire, ruby, or agate jewels. Of these, agates are the harder, but are more liable to crack, so that for heavy movements, and more especially those subjected to vibration or rough usage, sapphires or rubies should always be employed.

Some divergence of opinion exists as to the **best form of pivot** and jewel, but an angle of about 60° is commonly adopted for the former. For laboratory instruments subject to little rough usage a fine point will be found best, while for commercial work a more obtuse angle is to be preferred as being more durable. Fig. 13 shows an ordinary pattern of pivot and jewel.

A special form of pivoting was introduced some years ago by Evershed and Vignoles, suited to instruments likely to be subjected to particularly rough usage, such, for example, as portable cell-testing voltmeters. This consisted in a spherical pivot working in a spherical jewel ground to a larger radius, the two being pressed into contact by means of a light spring. Such a pivot is practically indestructible, but of course introduces many times the friction of the ordinary form, so that it is only applicable to those cases in which the

ratio of torque to weight is large (see p. 36), or where extreme accuracy is unnecessary.

The pivoting is always better in instruments in which the pointer swings in a horizontal plane, since nearly all the weight is then carried on one point which rests on the bottom of its jewel. The more nearly the axis approaches the vertical the less will be the friction; in fact, to ensure this the system may be supported on one pivot only (see p. 37).

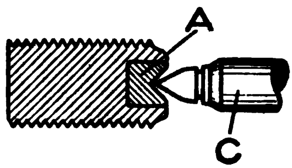


FIG. 13.—Typical Jewel and Pivot.

For switchboard instruments it is, as a rule, necessary that the pointer should move in a vertical plane, and for

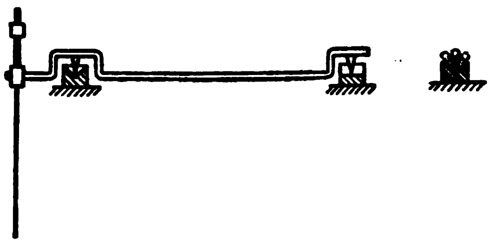


FIG. 14.—Needle Point and V Pivoting.

some instruments, such as electrostatic voltmeters, in which the working forces are small, the ordinary pivoting is unsatisfactory. In such cases, needle points resting on **hardened steel cups** or V's (see Fig. 14) are often used, and are quite durable, so long as provision is made for lifting them off when travelling, and the instrument is not subject to frequent and sudden overloads.

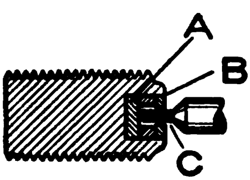


FIG. 15.—Jewel and Endstone.

Pivots of iridium were suggested years ago by Kelvin as being hard and not **liable to rust.** The difficulty of working them is great, and trouble from rust is not serious provided steel pivots are well polished and the instrument case is

reasonably damp-proof. It has recently been suggested that "jewels" of **tungsten** might be used. This metal is extremely hard, but it seems doubtful if any advantage would be gained by its use for this purpose.

When the weight of the moving parts is considerable and the working forces are large, the form of pivoting shown in Fig. 15 is sometimes employed. This is similar to the jewel and endstone of the clockmaker, and is satisfactory, so long as it is accurately made. For relays or graphic instruments subject to sudden overloads this arrangement has proved particularly useful.

It need hardly be pointed out how extremely important it is that the torque of an instrument should be as large as possible, in order to avoid **frictional errors.** At the same time, it is useless to obtain a high torque at the expense of increased weight of the moving system. In fact, the minimum satisfactory torque depends, other things being equal, upon the weight. In the case of a portable instrument the torque in centimetre-grammes for a 90° deflection should not be less than one-twentieth of the weight in grammes. For a switchboard instrument the figure should be increased to at least one-tenth, since the axis is usually horizontal, severe overloads have to be reckoned with, and a coarser point is usually adopted for the pivot.

As examples the following may be cited :—

A moving coil instrument had a weight of 2 gms. and a torque of 1·0 cm.-gm. In this case torque $= \frac{\text{weight}}{2}$, which is extremely good.

An induction ammeter had a weight of 30 gms. and a torque of 1·2 cm.-gm. for a 90° deflection. In this case torque $= \frac{\text{weight}}{25}$, which is insufficient for satisfactory working.

It is not always realised how great the stress on a sharp pivot may be, even with a comparatively small weight. With a pivot sharpened to a mathematical "point" the load per square inch would be infinitely great. While such a case

cannot arise in practice, Haskins[1] has calculated that in the case of a watt-hour meter the stress on a pivot of reasonable dimensions may amount to as much as 200 tons per square inch. Such being the case, the importance of care in the design and selection of pivots is evident.

It is not easy to give a definite figure for the **frictional torque** exerted by a pivot, since, when in good condition, the torque is usually so small as to be inappreciable, and when in bad condition the figure is of little value. However, several determinations of the retarding torque due to bearing friction have been made in the case of integrating meters; and, although not strictly comparable, they are of interest. One of the most complete investigations is that of Messrs. Fitch and Huber,[2] the instruments experimented with being American continuous current watt-hour meters. The bearing torque was found to be practically constant from rest upwards and, expressed as the ratio of torque to weight, varied from 0·000112 to 0·000147, the average being approximately 0·00013.

If this figure is applied to an indicating instrument having a ratio of torque to weight of ·065, the ratio of the frictional torque to the full scale working torque is $\frac{\cdot 00013}{\cdot 065}$, or $\frac{1}{500}$. That is to say, the frictional error would amount to $\frac{1}{5}$ division on a 100-division scale, or to $\frac{1}{100}$ in. in the case of a scale 5 ins. long. This result is of considerable interest as confirming the statement made above, and based upon experience, that the ratio of torque to weight should not be less than one-twentieth in the case of a portable instrument, or one-tenth in that of a switchboard instrument.

Whilst for most purposes two pivots are essential, a great reduction in friction is possible by the use of **one pivot alone,** as in the "unipivot" instruments of Paul (see p. 124), since when two are employed it is only on the unjustifiable assumption of perfect balance and exact levelling that the friction of the upper pivot can be neglected.

[1] *General Electric Review* (U.S.A.), Vol. 13, No. 9.
[2] *Bulletin of Bureau of Standards* (U.S.A.), Vol. 10, p. 161.

Damping.

The question of "dead-beatness" is somewhat complex, since it is governed not only by the amount of damping applied and the moment of inertia of the moving system, but also by the controlling force.

If an undamped instrument is set swinging, it will oscillate on either side of its point of rest, the amplitude and time of swing being constant (curve 1 in Fig. 16). If it is now slightly damped (by eddy currents, for example), the time of swing will still be constant, but will be greater than before, and the amplitude of each succeeding swing will be less, by a constant fraction, than the one preceding it (curves 2 and 3). As the damping is increased the "periodic time" becomes greater and greater, until at length it reaches a value such that the needle no longer flies past the point of rest, but stops at it (curve 4). The motion is then said to be **"aperiodic,"** and an instrument damped to just this extent is said to be "critically damped," or "dead-beat" in the strictest sense. If the damping is still further increased, the motion becomes "sluggish" (curve 5).

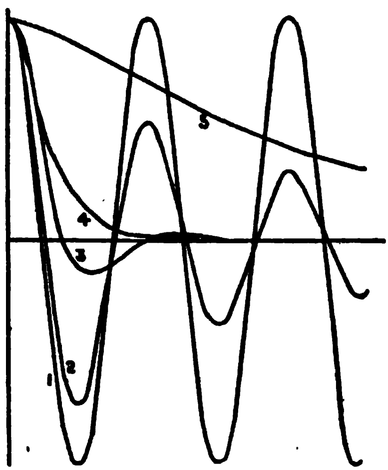


FIG. 16.—Damping Curves.

In the curves of Fig. 16 the moment of inertia of the moving parts and the controlling force are assumed to be constant, the damping alone being varied. This is what usually occurs in practice, since both the momentum and the working forces are fixed, once and for all, by various considerations, and the damping must be so adjusted as to give the best results.

A comparison of the curves will show that the pointer comes to rest in the shortest time when critically damped. This is invariably the case with any given system, but it is a condition which cannot always be attained in practice; and it will be noticed that, by the time the instrument giving curve 4 has come to rest, the amplitude of that giving curve 3 is so extremely small that there is not much to choose between them. It will also be seen that as the damping is increased the periodic time increases slightly at first and then much more rapidly.

The effect of successively decreasing the **controlling force** is shown in curves 1 to 5 of Fig. 17, from which it will be seen that for a given amount of damping there is always a particular control which gives critical damping (curve 3). If the damping is reduced below this the movement becomes sluggish (curves 4 and 5).

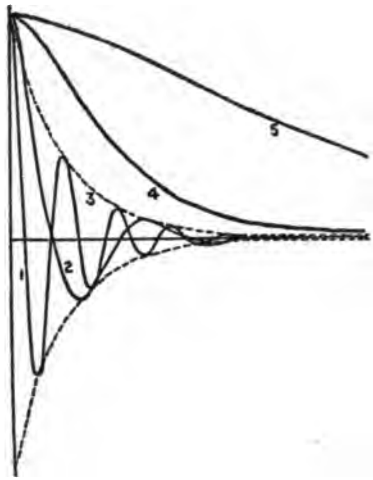


FIG. 17.—Damping Curves.

One interesting feature brought out by these curves is that, although the number of swings made before coming to rest decreases as the control is increased, the time taken is independent of this (so long as the control exceeds that giving critical damping), the peaks of all the curves touching the aperiodic curve (No. 3).

It is easy to determine how nearly a given instrument approaches the point of critical damping by noting by how much the pointer overshoots a reading as it flies up to it. This distance, divided into that between zero and the reading, is often called the "coefficient of damping." For most purposes, however, what is required of an instrument is that it should accurately follow rapid variations[1]; and, except

[1] In certain cases some sluggishness is essential, for example in the case of

perhaps in the case of a graphic instrument, slight overshooting of the correct reading is but a small disadvantage compared with the corresponding gain in what might be called "snappiness." In fact, an instrument which is critically damped labours under the disadvantage that it is difficult to detect frictional errors, should such exist.

All things considered, the best criterion is probably the **time taken in coming to rest at a given point.** The table gives some figures showing the results obtained in practice with instruments of various kinds, some being air-damped, and others damped by means of eddy currents. The measurements are in each case taken at a point 70 per cent. up the scale, the pointer being suddenly brought up to it, from zero, by switching on a current corresponding to that reading.

Class of Instrument.	Form of Damping.	Percentage by which the 70 per cent. point is overshot, starting from zero.	Time taken in coming to rest at the 70 per cent. point.
(1) Moving coil, portable	Eddies	2·5 per cent.	0·6 sec.
(2) " 8 ins. round	"	22 "	2·0 "
(3) Moving iron, 6 ins. round	Air	10 "	2·25 "
(4) " 8 ins. round	"	25 "	3·5 "
(5) Hot wire, 8 ins. round voltmeter	Eddies[1]	*Nil*	4·0 "
(6) Induction, 8 ins. round	"	10 per cent.	5·0 "
(7) Moving coil, large sector	"	50 "	6·0 "
(8) Moving iron, large sector	Air	55 "	7·0 "
(9) Moving iron, 8 ins. round	Oil	*Nil*	8·0 "

a plant driven by a slow-speed gas or oil engine. If each impulse is accurately followed the instrument is almost unreadable. With heavy damping, however, the instrument indicates the mean value.

[1] In a hot-wire instrument the damping is largely thermal, and depends upon the heat capacity of the hot wire. An ammeter of this pattern is always damped far beyond the critical value.

In the table, the first example—a standard testing instrument—is probably about as satisfactorily damped as could be wished. The remainder are switchboard instruments, those showing the worst results being large sector or edgewise patterns, 2½ secs. for a small instrument and 5 secs. for a large one may be considered satisfactory. No. 9 was purposely rendered sluggish, so as to damp out the pulsations of current due to a gas engine.

Another important feature of good damping lies in the protection which it affords to the moving parts (more particularly the pointer) against damage from sudden overloads. Moreover, by preventing excessive swinging to and fro it has the effect of prolonging the life of pivots and jewels during transit.

Damping devices usually depend upon one of three things:—

(1) Electrical eddy currents.

(2) Fluid friction.

(3) Air friction.

In moving coil permanent magnet instruments (p. 144) it is only necessary to construct the "former," which carries the winding, of copper or aluminium, in order to render instruments with moderately short pointers quite dead-beat by means of the **eddy currents** induced. With large sector and edgewise instruments, however, the damping is less satisfactory (see No. 7 in table). The disc or drum of induction instruments (p. 166), again, affords a ready means of damping by the use of a permanent magnet, although there is a tendency to sluggishness owing to the momentum of the disc (see No. 6 in table). Eddy current damping is also readily applicable to electrostatic and hot-wire instruments, but is less satisfactory with the moving iron and dynamometer types, since when used for continuous current the proximity of the strong permanent magnet considerably affects the readings and, although this can be allowed for in calibration, any weakening of the magnet, with time, will have its effect upon the readings. With alternating currents the field due to the winding gradually demagnetises the permanent magnet unless it is carefully shielded, and the method

is altogether inapplicable to such instruments when intended for use on both continuous and alternating current circuits.

The position of the damping magnet upon the disc is a matter of importance which does not always receive the attention it deserves. In Fig. 18, A represents the pole of the damping magnet and B the pivot about which the disc swings. The dotted lines represent the flow of the eddy currents. As the magnet is moved nearer to the edge of the disc the torque increases, owing to the increased radius, but subsequently decreases, owing to the rapidly increasing ohmic resistance caused by the eddy currents being crowded into a narrower space between A and the rim of the disc. Fig. 19 illustrates this, and shows the relationship between the torque and the position of the damping magnet, in a typical case. The torque can be expressed as :—

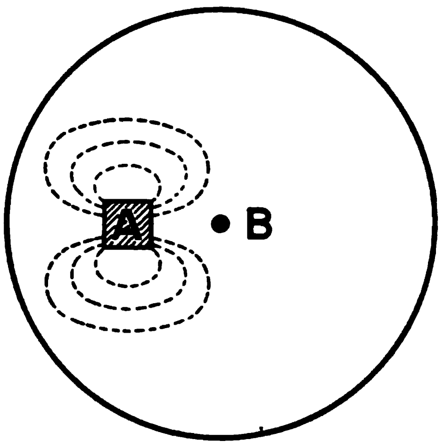


FIG. 18.—Brake Disc Damping.

$$\text{Torque} \propto \frac{B^2 r^2 \omega}{R},$$

where B is the flux density, r the radial distance of magnet pole from the centre of the disc, ω the angular velocity of the disc, and R the apparent resistance of the disc. The variation of R in the case of a disc of 8-cm. radius is shown in Fig. 19. It will be seen that the apparent resistance increases rapidly as the periphery is approached. The position of maximum torque usually corresponds to three-fourths or five-eighths of the radius of the disc from the centre (see upper curve, Fig. 19), thus showing that care

is necessary in determining the best position for the damping magnet.

A further point brought out by the equation is the importance of a strong field, and this applies to all forms of magnetic damping, whether by means of a disc or of a metal-former in a moving coil instrument (see also p. 64).

The oldest method, and the one still commonly used where the moving parts are heavy (*e.g.*, multicellular electrostatic

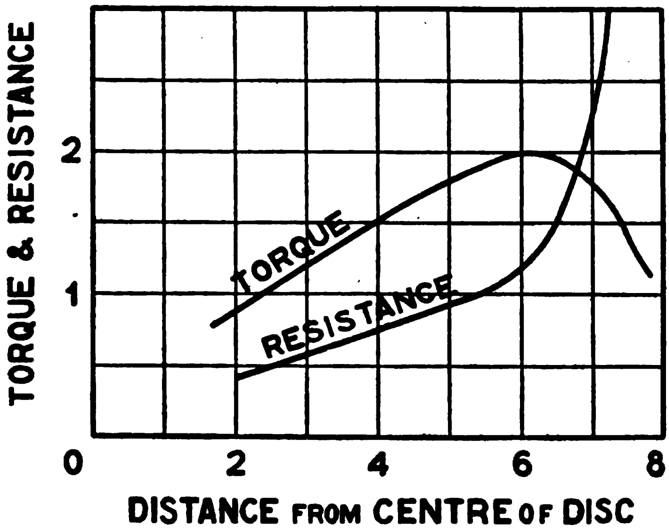


FIG. 19.—Brake Disc Damping. Effect of Magnet Position.

voltmeters) or where the working forces are great (*e.g.*, graphers), is **oil damping.** To be satisfactory the "paddle" should remain continually immersed, since, if it is withdrawn from the oil as the pointer deflects, some will adhere to the surface and "creeping" will result. If the axis of rotation is vertical a very efficient damper can be constructed on these lines, as shown in Fig. 20. Provided the fine wire carrying the paddle is in line with the axis of rotation, no creeping is noticeable, and the damping can be made as great as may be required.

An oil-damping arrangement suitable for an instrument

with a horizontal axis is shown in Fig. 21. The level of the oil is such that its surface is exactly in line with the axis of rotation, so that the arm carrying the paddle is always immersed to the same extent, and creeping is eliminated. Whatever precautions are taken, however, oil damping is only to be recommended when other forms are insufficient. A disadvantage of oil damping lies in the very great effect of changes of temperature on the viscosity of the oil and consequently on the damping. It has been proposed to overcome this to some extent by keeping the oil warm, electrically, by means of an adjustable resistance.

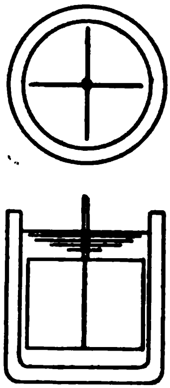


FIG. 20.—Oil Damper.

For commercial instruments other than the moving coil, and particularly for portable patterns, the best damping device is one based on **air friction.** A form of pneumatic damper is shown in plan in Fig. 22. The vane V swings in the double sector-shaped box, which it fits with as little clearance as possible. In Fig. 23 is shown a well-known form of damping piston. It passes along a curved cylinder, of round or rectangular section, without touching it at any point. There is not much to choose between these two systems; the former adds somewhat to the depth

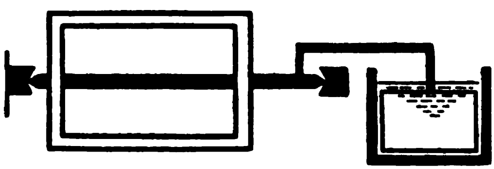


FIG. 21.—Oil Damper.

of the instrument, while the latter increases the weight. This, however, is of small importance, since it can be so arranged as to counterbalance the weight of the pointer. Nearly all the air-damping devices in use at the present day are based upon one or other of these two arrangements.

A damping vane carried on the pointer itself has been tried, but invariably leads to loss of balance, sooner or later.

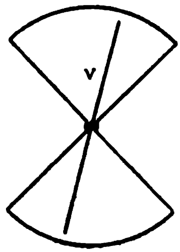


FIG. 22.—Air Damper.

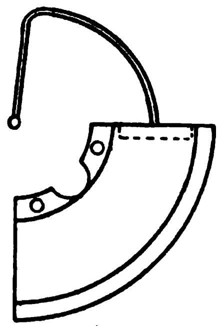


FIG. 23.—Air Damper.

Shunts.

The term "shunt" is commonly applied to a low resistance employed to divert a definite proportion of current from a measuring instrument, such as an ammeter. It is also, occasionally, used to indicate the pressure circuit of a wattmeter or watt-hour meter, thus causing confusion, and this latter use of the term is best avoided. The chief use of shunts is in the measurement of continuous current by means of permanent magnet moving coil instruments (p. 144). It is then possible to limit the current carried by the ammeter proper to a small fraction of an ampere, and it may be regarded as a low-reading voltmeter which **indicates the drop of pressure** over the shunt.

The table on p. 46 shows some of the instruments with which shunts are employed and the approximate current which usually passes through the indicator at full load, together with the usual pressure drop.

Shunts are also employed in connection with certain types of relay. These instruments are very similar to ammeters in their electrical properties, so that for the present purpose they may be classed as such. The figures given embrace both indicating and graphic types, the voltage drop in the latter being usually about double that in the former.

The essentials are constancy of resistance ratio at all temperatures, good heat dissipation, and absence of thermo-E.M.F.'s at the terminals. On alternating current circuits shunts must be designed for a definite self-induction ratio as well.

Type.	Amperes through Instrument.	Voltage Drop.	Application.
Ammeter, moving coil	0·05 to 0·25	0·05 to 0·15[1]	C.C.
„ moving iron	5·0 to 20·0	0·15 to 0·5	C.C. or A.C.
„ hot wire	5·0 to 20·0	0·1 to 0·5	C.C. or A.C.
„ dynamometer	5·0 to 25·0	0·1 to 0·5	C.C. or A.C.
Wattmeter, dynamometer	10·0 to 25·0	0·1 to 0·5	C.C. only.
Oscillograph, moving coil	0·1	1·0	A.C. or intermittent.
Ampere-hour meter, mercury motor	25·0 to 50·0	0·05 to 0·1	C.C. only.
„ „ „ electrolytic	0·05	1·0	C.C. only.
Potentiometer	*Nil*	0·15 to 1·5	C.C. or A.C.

The question of heat dissipation becomes of great importance in shunts dealing with large currents, particularly those having a considerable voltage drop, as, for example, for use with the potentiometer where the drop commonly reaches 1·5 volt at full load.

The well-known resistance alloys, eureka (or constantan) and manganin (or tarnac),[2] are very suitable for the construction of shunts. **Eureka,** composed of 60 per cent. copper and 40 per cent. nickel, has a temperature coefficient of only about 0·001 per cent. per degree Centigrade,[3] and is, therefore, negligible. But it has a high thermo-E.M.F. with copper—namely, 0·0046 volt per 100° C. **Manganin** contains 84 per cent. copper, 12 per cent. manganese, and 4 per cent. nickel. The temperature coefficient is also negligible (say 0·003 per cent. per degree Centigrade) and the thermo-E.M.F. with copper is extremely small (say 2

[1] 0·075 volts is the usual standard.

[2] See C. V. Drysdale, *Electrician*, Vol. 77, p. 632 (1916).

[3] Although the alteration of resistance with temperature is usually expressed in this way, the curve always bends over as the temperature is increased (see p. 292). For small changes of temperature, however, a straight line can be assumed.

micro-volts per 1° C.). It requires, however, special methods for soldering, in order to ensure constancy of resistance at the joints.

Other alloys which have a negligible temperature coefficient and a low thermo-E.M.F. with copper are an American material known as therlo and ferry (copper-nickel). Therlo requires careful ageing before use and is not very readily soldered, but is otherwise satisfactory. Chromic (a nickel-chrome alloy) has an exceptionally high specific resistance (93 michromes per centimetre cube, as compared with 40 for manganin), but a rather high temperature coefficient (·04 per cent. per degree Centigrade).

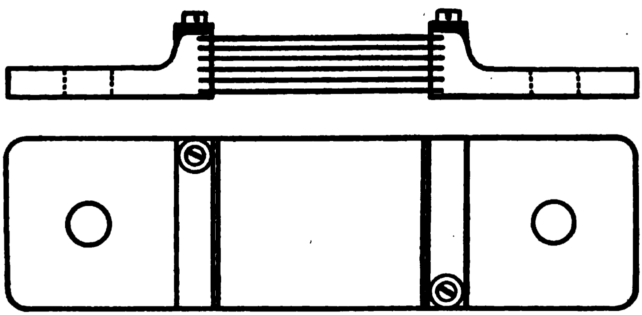


FIG. 24.—Typical Shunt.

A shunt, as commonly constructed, consists of thin sheet, say 0·5 to 1·0 mm. thick, cut up for the sake of compactness and convenience in mounting into a number of strips which are placed one above the other, with air-spaces between them, as indicated in Fig. 24. The total width of sheet (*i.e.*, the width of each strip multiplied by the number of strips) depends upon the current to be carried, while the length between the end blocks is dependent upon the voltage drop required.

Another construction which has been found satisfactory is that shown in Fig. 25, in which it will be seen that the resistance material is in the form of tubes instead of strips. Rod material has also been employed, but this has not much to recommend it.

In another alternative strip metal is used, but the strips are placed in a diagonal direction, resulting in a formation somewhat similar to the "louvre" form of ventilator. By this means a good circulation of air is obtained between the strips when the shunt is mounted horizontally with the strips in any plane.

The end blocks are usually of high conductivity cast bronze, or may be built up of drawn copper, and so arranged that the conductors or bus-bars can be clamped on both sides of the block, or even interleaved with it, so as to ensure ample **contact surface.** This is a matter of importance, since the heat produced by a poor joint may be

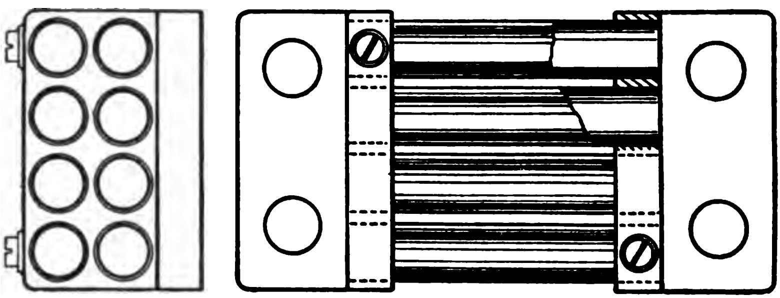


FIG. 25.—Shunt with Tubular Conductors.

greater than that due to the shunt resistance itself. Moreover, the thermal conductivity of the conductors bolted to the blocks is instrumental in dissipating a large part of the heat generated within the shunt.

The **temperature rise** of shunts is largely dependent on the position in which they are mounted, and they should always be so fixed as to permit a free passage of air between the leaves. This is well provided for, in the type shown in Fig. 24, when mounted on edge in a horizontal position, but the design shown in Fig. 25 is somewhat better in this respect, if the shunt has to be mounted vertically. Vertical mounting should, where possible, be avoided, since the heated air, rising past the upper terminal, is almost certain to cause this to get hotter than the lower one and may give rise to

an unbalanced **thermo-E.M.F.** which appreciably affects the instrument readings (see p. 14). The Peltier effect aggravates this, as has been pointed out by Melsom, causing the positive terminal to heat much more than the negative. For this reason it should, if possible, be placed uppermost.

The presence of an error due to a thermo-E.M.F. can be detected by breaking the main circuit, when the pointer, instead of returning to zero, still shows a slight deflection to one side or the other, and only gradually returns to zero as the shunt cools down. If this occurs, the ammeter reading should be corrected by adding or subtracting, as

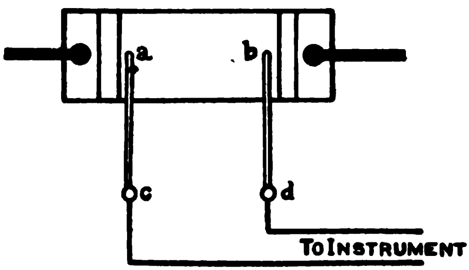


FIG. 26.—Elimination of Thermal Error in Shunt.

the case may be, the deflection observed immediately after opening the circuit.

The error can be entirely eliminated by connecting the leads from the instrument, not to the shunt-blocks direct, but to the ends of two strips or wires made of the same metal as the shunt and soldered to it. This arrangement is shown in Fig. 26. If the strips *a c* and *b d* are sufficiently long to ensure that the points *c* and *d* are always at the same temperature (*i.e.*, that of the surrounding atmosphere), independently of the temperature of *a* and *b*, it is clear that no thermo-E.M.F. is possible. The points of attachment (*a* and *b*) need not necessarily be on the leaves of the shunt, as in the figure, but can be on the shunt-blocks, assuming, as will almost always be the case, that the temperature of *a* and *b* is the same as that of the respective

points of junction between the leaves and the blocks. When this is so, the two equal and opposite thermo-E.M.F.'s cancel each other.

If the wires which connect the shunt to the instrument are attached to the end blocks, as is usually the case (see Fig. 24), any variation in the **resistance of the shunt joints** will affect the reading of the ammeter. The greatest care, therefore, is necessary to ensure perfect soldering. If the instrument leads are connected to two points on the shunt strip itself (as shown at *a* and *b*, Fig. 26), a variation in this resistance will not affect the reading. It will be seen, however, that this advantage is only possessed by the latter arrange ment in the case of a shunt composed of a single strip, since with more than one the distribution of the current amongst them will depend upon the relative resistances of the various joints.

Allowance should be made for the fact that bus-bars expand and contract in working owing to changes of temperature. If the shunt strips are not excessively thick, these will usually buckle sufficiently to allow for any such movement, but if considered necessary the shunt strips may be corrugated transversely.

When it is essential that a **shunt shall be non-inductive,**[1] so that the voltage drop at a definite current is the same whether used on continuous current or alternating current of any frequency, it is necessary somewhat to modify the construction. Firstly, it may be noted that the employment of a high-current density leads to a reduction in the length of the strip and with it of the self-induction. For this reason forced cooling by water or oil is advantageous, since it permits a much higher current density without overheating. The strip may also be doubled back at its centre, so that the end blocks are brought quite close together, in which case the self-induction will be negligible up to frequencies of, say, 500 cycles per second.

An ingenious arrangement of non-inductive standard

[1] For a full discussion see F. B. Silshee, *Bulletin of American Bureau of Standards*, No. 281 (1916).

shunt, adopted by the National Physical Laboratory,[1] is illustrated in Fig. 27. The shunt (M) is tubular, and is cooled by water passing continuously through it from W_1 to W_2. The instrument leads pass back parallel to and close against the shunt tube. T_1 and T_2 represent the main terminals, while t_1 and t_2 are the potential points, brought back to a central point, t_3, by means of concentric tubes, so that the self-induction becomes negligibly small.

In a shunt designed by Drysdale, two concentric cylinders of manganin are employed, the current being led down one

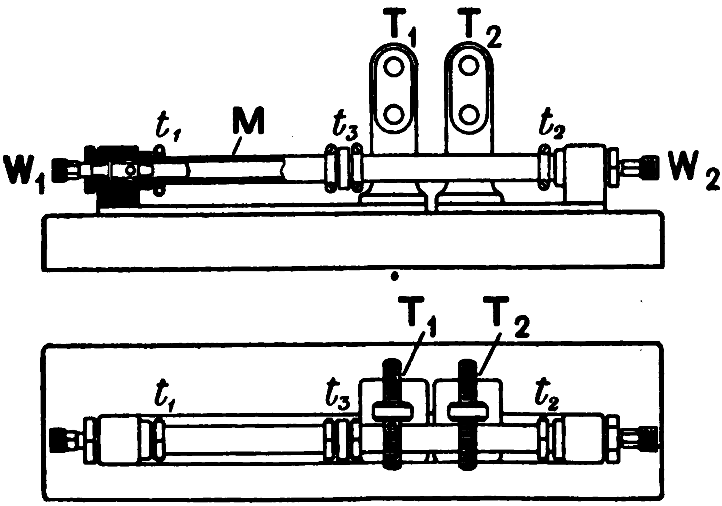


FIG. 27.—Non-inductive Water-cooled Shunt.

and up the other, thus reducing the self-induction to a negligible quantity Cooling is effected by a water-cooled oil-bath, the contents being stirred by means of a rotating fan.

In some cases, such as, for example, with moving iron instruments, it is desirable that the shunts should have a **similar time constant to that of the instrument,**[2] so that the shunting ratio may be independent of the frequency of the circuit on which it is used. A construction employed

[1] A description of this shunt is given in a paper by Paterson and Rayner, *Journal Inst. Elec. Engineers*, Vol. 42, p. 455.

[2] See also p. 143.

by Everett, Edgcumbe & Co. for this purpose is illustrated in Fig. 28, from which it will be seen that the shunt is passed through a tubular iron screen, A, of which the seam S is not entirely closed. By adjusting the width of the opening S, the inductive drop of the shunt may be varied until the readings of the instrument connected to it are unaffected by changes of frequency.

There is some difficulty in specifying the maximum **allowable temperature rise** which may, reasonably, be expected from a shunt, since the final temperature depends almost as much on the conditions of mounting as on the shunt itself. It is, of course, well recognised that shunts should never be worked at such a temperature that there is any

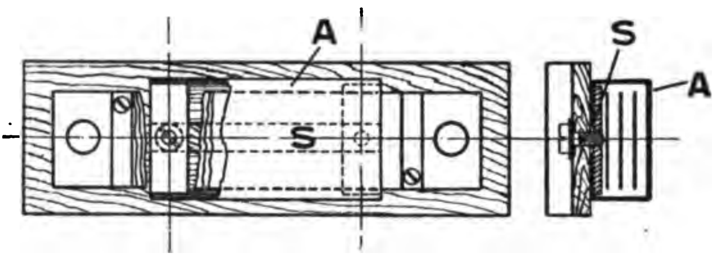


FIG. 28.—Shunt with Adjustable Self-inductance.

risk of the solder melting, and probably a temperature of 100° C. under continuous full load is as high as can be considered good practice, and a rise of 80° C. above the surrounding temperature is commonly specified. It will often be found, however, that the conditions on the switchboard, owing to high current density in the bus-bars, poor joints, adjacent shunts or resistances, etc., may cause the temperature rise to be much greater than that due to the shunt itself. When a temperature of over 100° C. is found, the surrounding gear should be carefully examined to locate any overheating.

The joints between bus-bars and shunt blocks should be so designed that the current density does not exceed 200 amperes per square inch of contact area, and if carefully

erected, the voltage drop across each joint at full load should not exceed 0·005 volt.

Multiplying Resistances.

Just as a shunt is employed to increase the range of an ammeter, so in the case of voltmeters and the pressure circuits of wattmeters or watt-hour meters an increase of range is obtained by connecting a high resistance in series with the winding. This absorbs a large part of the voltage and keeps the pressure on the instrument winding within convenient limits. The value of the resistance employed depends on the voltage to be dealt with and the current

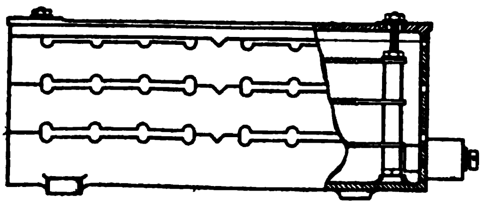


FIG. 29.—External Multiplying Resistance Box.

taken by the instrument, and usually varies from 500 to 10,000 ohms per 100 volts.

Thermo-electric E.M.F.'s are quite negligible in this connection, but only the very smallest possible **change of resistance with varying temperature** is allowable. Such resistances are, therefore, usually made up of eureka or manganin (see p. 46), the one being as good as the other for the purpose. The wire is usually covered with a double layer of silk and is wound either on porcelain bobbins or on flat plates of micanite or other high grade insulating material. Porcelain bobbins have the disadvantage that the **heat generated** in the resistance is not readily dissipated, unless a single layer of wire is sufficient, and even then the heat radiation is not good, and such a construction is only suitable for small powers. The amount of heat to be dissipated determines whether the multiplying resistance can best be

placed (1) inside the case or (2) at the back of the case, or (3) in an external box. To place the resistance inside or attached to the instrument makes for convenience and safety in use, so that, where the power dissipated allows of it, this arrangement is generally adopted. Up to about 5 watts the resistance can usually be placed inside the case, and up to 15 watts on the back. For heavier loadings than this the external type of resistance should be used,[1] and may well be arranged somewhat as shown in Fig. 29. The resistance wire is wound on cards of micanite, and the ventilation is so good that it is possible to dissipate 60 or 80 watts in about half the space occupied by an 8-in. dial switchboard instrument. When using external resistances, it is well to put a part of the resistance in the instrument, as this reduces the risk of damage by accidentally connecting it up without its multiplying resistance box.

It is often of importance that the self-induction and capacity of a multiplying resistance should be negligible. A simple way of **rendering a coil practically non-inductive** is to wind on two strands of wire at once. The commencing or inner ends are joined together while the outer or finishing ends are joined to the terminals. Thus, the current flows through the two wires in opposite directions; and, as they lie close together, the magnetising force due to the current in one is cancelled by that in the other, and the self-induction is almost entirely eliminated. The method is only applicable, however, to coils for low voltages, owing to the fact that the full terminal potential difference exists between two adjacent wires, so that the risk of breakdown is considerable. For the same reason, the capacity is comparatively high.

A similar result may be obtained by winding the coil in two sections in parallel, the one having a right-handed and the other a left-handed winding. This is equivalent to a simple coil as regards capacity and freedom from risk of breakdown,

[1] For moderately heavy loadings, up to say 12 watts, a useful alternative, sometimes applicable, is to place the resistance within the case of the instrument, but in a ventilated compartment separated by a partition from that containing the measuring system.

but does not lend itself to the winding of high resistances, owing to the necessity for connecting in parallel.

Both disadvantages can be removed by winding the coil in the usual manner, but in sections, and reversing the direction of winding as each section is commenced. The **capacity** of a resistance consisting of n sections is $\frac{1}{n^2}$ times that of a similar resistance wound in a single coil; moreover, the maximum difference of potential between neighbouring wires is $\frac{1}{n}$ of the full voltage.

In modern practice, however, resistance coils or bobbins are seldom used, as self-induction is practically eliminated by winding the wire on a flat card or frame, either continuously or in sections (see Fig. 29). The cooling surface is then a maximum, and the self-induction and capacity negligible for most purposes. In another alternative construction the resistance wire is woven into a flat strip by means of silk threads running at right angles to it (Duddell-Mather).

Permanent Magnets.

Since the **magnetising force** required to produce a certain flux density in an electro-magnet is proportional to the length of the magnetic path,[1] it is usual to express the magnetising force in ampere turns per centimetre (or other unit) of magnetic path. If the path is not entirely through iron or steel, but is intercepted for a portion of its length by air or other non-magnetic material, the ampere turns per centimetre length of this portion will be 0·8 $\left(\text{accurately } \frac{10}{4\pi}\right)$ times the flux density in C.G.S. lines per square centimetre of cross section. It is, therefore, convenient to express magnetising forces in terms of ampere turns per 1·257 $\left(\frac{4\pi}{10}\right)$ cm. of path,[2] since for non-magnetic materials this is equal

[1] In the case of a ring the length of magnetic path may be taken as the mean perimeter of the ring.

[2] It is of interest to note that 1·257 cm. is very nearly ½ in.

to the resulting flux density in lines of force per square centimetre of cross section.

In what follows, therefore, flux density is expressed in lines per square centimetre (denoted by the letter B), while magne-

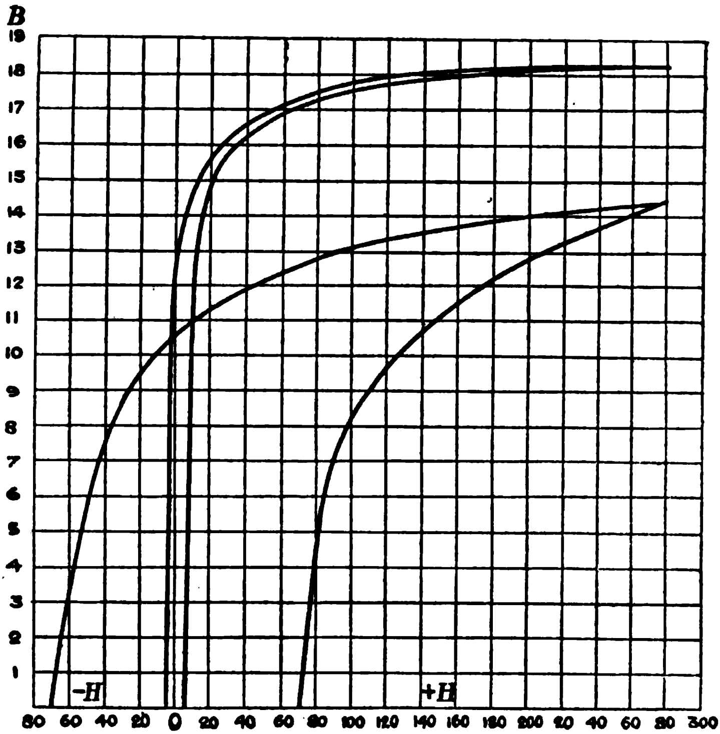


Fig. 30.—Magnetisation Curves of Iron and Steel.

tising forces are given in ampere turns per 1·257 cm. length of path (denoted by H). The ratio $\frac{B}{H}$, which is the **permeability,** is always unity for an air-gap, but is something greater for steel or iron, depending upon the composition, mode of preparation, and degree of magnetisation attained.

In Fig. 30 are shown the results of some magnetisation tests made on two rings, one of hardened magnet steel (lower

curve) and the other of soft iron, such as is employed in transformer construction (upper curve).

These curves show that after the magnetising force has been removed the soft iron is actually left in a more highly magnetised state than the hard steel, but that the application of a comparatively small demagnetising force is sufficient to destroy the magnetism in it. The relative stability of the remanent magnetisation of the two specimens is shown by the demagnetising forces *OH*, which are known as the **coercivities** or coercive forces of the materials used.

Design of Magnets.

Owing to a number of variable factors, a permanent magnet does not lend itself to accurate calculation in the

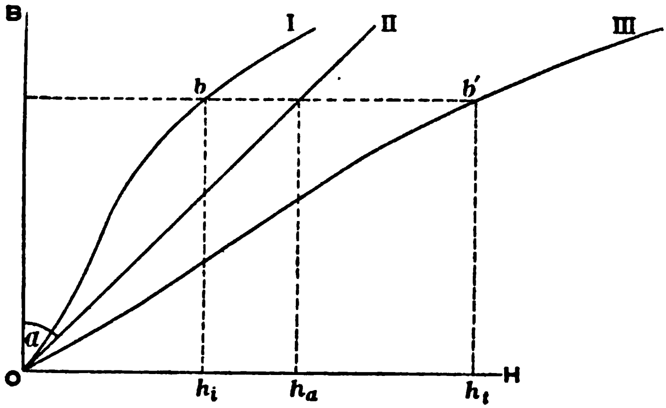


FIG. 31.—Magnetisation Curves for Steel with Air-gap.

same way as an electro-magnet. The following method, however, leads to useful results[1] :—

Let Curve I. in Fig. 31 represent the magnetisation curve of a ring of soft iron without joint, both the flux density B and the magnetising force H being expressed in C.G.S. units. If, now, a slit is cut in the ring so as to interpose an air-gap, the $\frac{B}{H}$ curve can be predicted as follows. In the first instance

[1] "Predetermination of the Residual Flux in Magnets," by Kenelm Edgcumbe, *Electrician*, Vol. 75, p. 546 (1915).

let the following conditions, though impossible in practice, be assumed for the sake of simplicity :—

Mean length of iron path, 1 cm.
" " air " 1 cm.
Area of iron and air paths equal.
Scale chosen for B the same as that for H.

Since the length of the air-gap is 1 cm., the value of H will be equal to the density B produced by it; that is, the $\frac{B}{H}$ curve for the air-gap will be a straight line making an angle of 45° with the base (Curve II.). Then the magnetising force required for a given flux density (b) in the iron will be Oh_i for the iron plus Oh_a for the air, that is Oh_t. This gives a point b' on the new $\frac{B}{H}$ curve (III.). In the same way a number of points can be found (giving Curve III.) such that the horizontal distance of each point from the sloping line (II.) is the same as that of each corresponding point on the original curve (I.) from the vertical line OB.

If the length and area of the air-gap are not equal to those of the iron path, and if B is the flux density in the iron, then the slope of Curve II. will, no longer, be unity. It is, in fact, such that—

$$Tan\ a = \frac{\text{Length of air-gap} \times \text{area of iron path}}{\text{Length of iron path} \times \text{area of air-gap}}.$$

If, again, the scales chosen for B and H are not the same, but are such that a single division on the sectional paper corresponds to a magnetic density of b and a magnetising force of h, then the slope of Curve II. must be such that—

$$Tan\ a = \frac{\text{Length of air-gap} \times \text{area of iron path}}{\text{Length of iron path} \times \text{area of air-gap}} \times \frac{b}{h}.$$

Applying the same reasoning to a permanent magnet, we have Fig. 32. Curve I. represents one-half of a hysteresis loop for a steel ring, without joint. If an air-gap is introduced of area and length equal to that of the steel, the loop III.

will be obtained. This is drawn, as before, by setting off horizontal distances from the sloping line (II.) equal to the distances of corresponding points on Curve I. from the vertical line *OB*. The slope of the line will again be such that—

$$Tan\ a = \frac{\text{Length of air-gap} \times \text{area of steel path}}{\text{Length of steel path} \times \text{area of air-gap}} \times \frac{b}{h}.$$

From an inspection of Curve III., it will be seen that the residual magnetic density has been reduced from b to b_1,

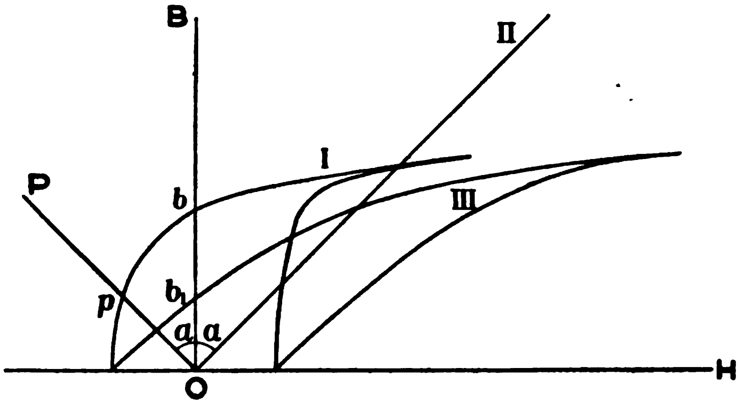


FIG. 32.—Hysteresis Curves for Steel with Air-gap.

by the introduction of the air-gap, thus showing its effect in reducing the " strength " of a permanent magnet.

The quantity *tan a* is often spoken of as the "**self-demagnetisation coefficient,**" and although not so readily calculated for **bar magnets,** is applicable to them also. For example, in the case of a round bar magnet 10 diameters long the coefficient is 0·2, if 15 diameters long it is 0·1, if 100 diameters long it is ·005, and so on. This enables a bar magnet to be dealt with in much the same way as a ring or horseshoe magnet, except that the flux density will vary along its length to a greater extent.

If it is desired, merely, to determine the **residual flux density** (*i.e.* the point b_1) this can be done without its being

necessary to draw Curve III. at all. A sloping line, O P, is drawn to the left of the vertical at an angle, a, determined as before. The point (p) at which this line cuts the curve corresponds to the residual flux density b_1.

In the case of a permanent magnet it is only the portion of the curve to the left of the vertical line which concerns us, and this part is shown to a larger scale in Fig. 33. In the case of a closed ring the remanent flux density will be b. If an air-gap is introduced, the remanent flux density will fall to b_1. Even this value b_1 is unstable, and is liable to be further reduced by vibration, heating, etc. To gain an idea of what takes place, the steel may be looked upon as possessing a magneto-motive force of its own, equal, approximately, to that necessary to demagnetise it (*i.e.*, Oh_1). If the density has been reduced by its treatment, say, from b_1 to b_2, the air-gap will then require a magnetising force of Oh_2, and the steel one of $h_1\,h_3$. But the total magneto-motive force available is Oh_1, so that there still remains the amount $h_2\,h_3$ as a "stand-by," or safety factor, against further demagnetisation.

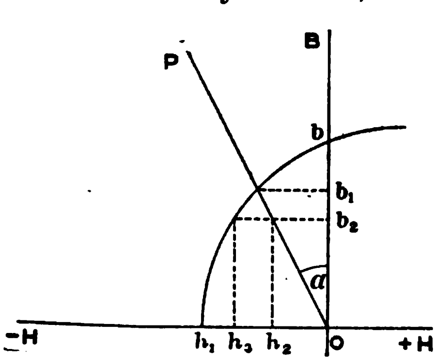


FIG. 33.—Determination of Constants of Permanent Magnet.

It will be seen that the more b_1 is reduced (that is, the lower b_2) the greater is the safety factor ($h_2\,h_3$) protecting the magnet against further demagnetisation. This explains the advantage of the artificial "**ageing**" **or** "**maturing**" of permanent magnets (see p. 67).

Magnetic leakage has been neglected in the preceding treatment, since it is difficult to predetermine and for well-designed magnetic circuits introduces a disturbance which is small compared with other variables. Its effect is to cause the density in the steel to be greater, for a given air-gap density,

than that calculated from the relative sectional areas; that is to say, the slope of Curve II. (Fig. 32) is reduced. The greater the reluctance of the air-gap, other things being equal, the greater will be the leakage.

An **example** may make the application of this method clearer. Let the following dimensions, which are taken from the magnetic circuit of an actual moving coil instrument,[1] be assumed:—

Length of path in magnet, 224 mms.
Cross section of magnet, 390 sq. mms.
Total length of air-gap, 1·73 mm.
Cross section of air-gap, 910 sq. mms.

$$Tan\ a = \frac{1{\cdot}73 \times 390}{224 \times 910} = 0{\cdot}0033.$$

To apply this value to the $\frac{B}{H}$ curve given in Fig. 30, it must be multiplied by the ratio of the scales chosen for B and H, namely 50, so that—

$$Tan\ a = 0{\cdot}165.$$

If a line making this angle with the vertical is drawn through the origin (as in Fig. 33) it will be found to cut the curve at the point B = 8,800, indicating that, neglecting leakage, a magnetic circuit of the given dimensions, using this particular brand of steel, might be expected to show a remanent magnetic density of 8,800 lines per square centimetre in the steel. This calculation neglects the reluctance of the core, pole pieces, etc., and also any ageing to which the magnet would, doubtless, be submitted before use.

Allowing a reduction of 25 per cent. for these causes, the effective density in the steel becomes 8,800 × ·75 = 6,600. The measured value, as taken from the paper cited, is 6,500.

In many cases, it is only the value of the remanent magnetisation (*Br*) and the coercive force (*Hc*) that are known for the brand of steel used, and it therefore becomes of importance to be able to predetermine the remanent flux from these constants. This can be done with sufficient accuracy, for most purposes, by assuming that the descending branch of the hysteresis loop, shown in Fig. 33, forms part

[1] From a paper by Fitch and Huber, *Bulletin of Bureau of Standards* (U.S.A.), Vol. 7, No. 163.

of an ellipse of which Ob and Oh_1 are the half-axes. If this is the case, it is easy to find a scale to which to plot B and H, such that the $\frac{B}{H}$ curve becomes a circle as shown in Fig. 34. This will be the case if the same length on the sectional paper represents a magnetising force of Hc and a magnetic density of Br, Hc and Br being the constants for the particular brand

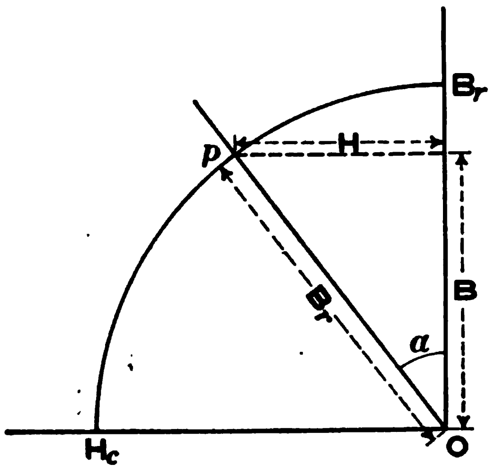


FIG. 34.—Determination of Constants of Permanent Magnet.

of steel used. Then, as before, calculating the angle from the formula—

$$Tan\ a = \frac{\text{Length of air-gap} \times \text{area of steel path}}{\text{Length of steel path} \times \text{area of air-gap}},$$

let
$$R = \frac{tan\ a \times Br}{Hc}.$$

If B (Fig. 34) is the flux density which it is desired to calculate and H the corresponding magnetising force, we have—

$$\frac{H}{B} = R, \text{ or } H = BR.$$

Also, since the curve is assumed to form part of a circle,

$B^2 + H^2 = Br^2$. Hence $B^2 + (BR)^2 = Br^2$, or $B^2 = Br^2/(1 + R^2)$,

so that
$$B = \frac{Br}{\sqrt{1 + R^2}}.$$

In this way, from a knowledge of the constants of the steel (*i.e.* Br and Hc) it is possible, roughly, to forecast the flux density for any given dimensions of magnet and air-gap.

In many cases it is the question of an **increase or decrease in the flux due to a change in the dimensions** which has to be studied, rather than its absolute value. In this case, if B_1, R_1, refer to the existing conditions and B_2, R_2, to the dimensions contemplated, then—

$$\frac{B_1}{B_2} = \sqrt{\frac{1 + R_2^2}{1 + R_1^2}},$$

or

$$B_2 = B_1 \sqrt{\frac{1 + R_1^2}{1 + R_2^2}}.$$

Applying this formula to the magnet already mentioned, the effect of doubling the length of the air-gap, keeping all other dimensions unchanged, can be calculated as follows :—

$R_1 = 0{\cdot}505$ and $R_1^2 = 0{\cdot}254$;
$R_2 = 0{\cdot}505 \times 2 = 1{\cdot}01$ and $R_2^2 = 1{\cdot}02$.

B_1 was found to be 6,500, so that—

$$B_2 = 6{,}500 \times \sqrt{\frac{1{\cdot}254}{2{\cdot}02}} = 5{,}130.$$

That is to say, in this case, doubling the air-gap has only reduced the flux by a little over 20 per cent.

As a further example a meter damping magnet, without pole pieces, may be taken. The dimensions in a certain meter were[1] :—

Length of magnet path, 181 mms.
Cross section of magnet path, 220 sq. mms.
Length of air-gap, 2·9 mms.
Cross section of air-gap, 310 mms.

[1] Fitch and Huber, *Bulletin of Bureau of Standards* (U.S.A.), Vol. 10. No. 207.

Hence, assuming the same steel constants as before,—

$$Tan\ a = 1{\cdot}14;$$
$$R_1 = 1{\cdot}74 \text{ and } R_1^2 = 3{\cdot}0;$$
$$R_2 = 1{\cdot}74 \times 2 = 3{\cdot}48 \text{ and } R_2^2 = 12{\cdot}1.$$

B_1 was found by experiment to be 3,700, so that—

$$B_2 = 3{,}700 \sqrt{\frac{1 + 3{\cdot}0}{1 + 12{\cdot}1}} = 2{,}050.$$

That is to say, doubling the length of air-gap results in a reduction of flux by 45 per cent. in this case.

The determination of this reduction (45 per cent. in the one case and 20 per cent. in the other) is of considerable importance, since it settles whether there is any advantage to be gained by **increasing the air-gap** in a given design of magnet. Taking the first case (*i.e.*, the moving coil instrument), doubling the length of the air-gap would enable twice the amount of the wire to be wound on the coil, which in the case of a voltmeter (the resistance being generally unimportant) would mean increasing the sensitiveness in the proportion of $\frac{5{,}130 \times 2}{6{,}500}$, that is by nearly 60 per cent.[1] Or, if preferred, the control could be increased by this amount, leaving the sensitiveness as before. With an ammeter movement (a milli-voltmeter) the advantage would be smaller owing to the effect of spring and other "idle" resistances (see p. 33).

The question of **damping** (see also p. 41) has to be considered. The damping torque is proportional to B^2t, where B is the air-gap flux density, and t the thickness of the metal-former. If the air-gap is doubled in length, t might reasonably be doubled also, so that doubling the air-gap increases the damping torque in the ratio $\frac{5{,}130^2 \times 2}{6{,}500^2}$, or by nearly 25 per cent. Although the torque is increased by this amount, it must be remembered that the moment of

[1] It has been assumed throughout that the air-gap flux density is proportional to that in the steel, but, in practice, any increase in the length of air-gap increases the leakage to some small extent.

inertia, to say nothing of the weight on the pivots, is also increased, so that whether the damping is improved or the reverse depends upon whether the weight of coil, winding, pointer, etc., forms a large part of the whole or not.

In the case of the meter magnet cited, there is no winding to be considered, and it is only the damping torque which enters into the question. In this case the relative damping torques are $2{,}050^2 \times 2 : 3{,}700^2$. That is to say, doubling the length of the air-gap and the thickness of the disc *reduces* the damping torque by nearly 40 per cent. Besides this, the weight of the disc would be doubled. A comparison of these figures shows how important it is to calculate each particular case, if the best results are to be obtained.

As the result of experience, it may be said that the **flux density in the steel** of a magnet lies, as a rule, between 1,000 and 6,000, the former being a poor, and the latter a very high, figure. The corresponding figures for the density in the air-gap may be taken as 500 and 2,500.

The following "golden rule" should be followed in the design of all instrument magnets :—

Make the constant—

$$\frac{\text{Length of magnet} \times \text{area of air-gap}}{\text{Area of magnet} \times \text{length of air-gap}}$$

as large as possible for a permanent magnet (certainly not less than 100) and as small as possible for an electro-magnet (where minimum hysteresis is aimed at).

Selection of Material.

Tool steel, which contains about 1 per cent. of carbon, is much superior to common iron or mild steel in coercive force, and may be considerably improved by hardening. It is now generally agreed that the most suitable kind of steel for permanent magnets is one containing from 5 to 8 per cent. of **tungsten. Chromium** (2 to $2\frac{1}{2}$ per cent.), **vanadium** (0·3 to 1 per cent.), **and silicon** are also useful in small proportions.[1]

[1] See also Margaret B. Moir, *Electrician*, Dec. 25th, 1914, p. 385, and F. C. Kelley, *Electrical Review*, Vol. 81, p. 166 (1917).

It was proposed by B. O. Pearce,[1] of Harvard, U.S.A., to employ hardened **cast iron** for magnets; and, as the result of experiments undertaken by him in America and by Albert Campbell in this country, there would appear to be a field for such magnets, although up to the present they have not been adopted for instrument work.

The following figures are derived from a paper by S. P. Thompson[2]:—

Material.	Coercive Force.	Permanent Density.
Softest iron	0·44	10,110
Low carbon steel	3·4	7,850
High „ „	58·0	8,100
Allevard (tungsten) steel (1)	26·0	11,320
„ „ „ (2)	73·0	10,060
Bohlers steel (1)	34·0	9,920
„ „ (2)	75·0	7,540
Remys tungsten steel (1)	63·0	10,180
„ „ „ (2)	77·0	10,060
Medium „ „	58·8	7,190
Chilled cast iron	52·5	2,740
Grey „ „	13·7	3,140
Chrome steel (1)	52·5	8,660
„ „ (2)	22·0	12,950
„ „ (3)	56·0	3,590

Both the coercive force and remanent density vary greatly, so that it is essential to obtain figures from the actual brand of material in use. As a possible ideal S. P. Thompson gives a coercive force of 80 and a remanent density of 10,000. It will be seen from the table that this is already closely approached by some of the tungsten steels on the market, and recently some German chrome steels have shown coercivities of 63 and densities of 10,000.[3]

The heat treatment is also of great importance, and depends upon the composition of the steel.[4] In a general way, it

[1] *Am. Acad. Proc.*, Vol. 22, p. 701 (April, 1905), and *Electrical Review* (New York), Sept. 15th, 1905, p. 411.
[2] *Proceedings of Physical Society* (London), Vol. 27, p. 179 (1915).
[3] *Elektrotechnische Zeitschrift*, Vol. 44, p. 592 (1916).
[4] See S. P. Thompson, *Journal Inst. Elec. Engineers*, Vol. 50, p. 80 (1912).

may be said that the metal should be forged at as low a temperature as possible, heated just above its temperature of recalescence (usually to 800° or 900° C.), and quenched.

Magnetisation.

This is now carried out by electrical means, either by passing a current through a winding threaded on the magnet, or by placing the unmagnetised steel across the poles of a powerful electro-magnet in such a way that the lines of force pass through its entire length. The latter method is generally more convenient, but has the disadvantage that it is not applicable to magnets whose poles are only separated by a very narrow gap.

With the first mentioned method, as it is not necessary to maintain the magnetising current for more than a fraction of a second, very high-current densities may be employed.[1] The coil can be connected, in series with an overload circuit-breaker, directly across the mains from a fairly large continuous current generator, giving 100 to 250 volts. Before the short circuit can do any damage the circuit-breaker opens and interrupts it. The operation should be repeated until there is no further increase in the magnetisation, this state usually being attained after three short circuits have been made. Some authorities maintain, on the other hand, that the current should be reduced slowly to zero.

A magnet prepared by either of the above methods may be used without further treatment in those instances where slight subsequent deterioration is immaterial, but for most instrument work constancy is of importance, and "**ageing**" or maturing is essential. To this end, the strength may be reduced, by means of alternating current, to about 80 per cent. of its initial value, the magnet then being stored for at least a month with its pole pieces in place. During this time it is advisable to keep a record of its strength, and if a variation of more than about ½ per cent. is detected during this time, it may be taken as evidence of unsatisfactory

[1] Ten to twenty turns of copper wire about ⅛ in. diameter are suitable for most instrument magnets, and a magnetising force of 200 to 300 ampere turns per centimetre length of steel path will be found ample.

composition or treatment of the steel. Some makers hasten the "ageing" process by steaming or boiling the magnets in oil for several hours. This, while not so convenient as alternating current, gives good results.

Measurement of Field Strength.

There are four principal methods of testing instrument magnets :—

(1) By means of a reflecting ballistic galvanometer ;
(2) By the Grassot flux meter ;
(3) By means of a spiral of bismuth ;
(4) By applying the magnet to a moving coil movement.

The **ballistic method** is the most accurate, and if permanently set up is fairly convenient, although possibly more suited to the laboratory than to the test room.

The **Grassot flux meter** consists of a moving coil galvanometer, with pointer, in which the mechanical control is reduced to a negligible quantity. If connected to a search coil the movement of the pointer is proportional to the product of the number of turns into the magnetic lines cut when the coil is withdrawn from a magnet pole, and the scale can be graduated accordingly. From a knowledge of the area and number of turns on the coil the field strength can be calculated. The deflection, which is permanent as distinguished from the "throw" of a ballistic galvanometer, is almost independent of the rate at which the coil is withdrawn and, within limits, of the coil and galvanometer resistance also. This instrument is very convenient for testing permanent and other magnets so long as the shape is such that the search coil can be withdrawn, which is not always the case.

Bismuth has the property of increasing greatly in resistance when placed in a magnetic field. A length of about 3 ft. of bismuth wire can be coiled up non-inductively into a flat spiral capable of being placed in an air-gap. Such a coil having a resistance of 10 ohms increases to nearly 15 ohms when placed in a field of $B = 10{,}000$, and a curve connecting resistance and flux density can be plotted.

The wire has a considerable resistance-temperature coefficient, and the effect of the magnetic field also depends upon temperature. The method is of little value for densities of less than 2,000 lines per square centimetre.

The simplest and most satisfactory method, in the majority of cases, consists in **applying the magnet** to be tested **to a moving coil movement** (fitted with standard pole pieces and core) through which a known current can be passed. The scale of either the ammeter or the movement can be marked off directly in terms of flux density.

In applying any of these methods, care must be taken that all joints in the magnetic circuit are good. The pole pieces, etc., should be as like those with which the magnet is to be used as possible, in order that the leakage may be the same in each case.

Calculation of Instrument Windings.

The ideal to be aimed at in all electrical measuring instruments is maximum torque consistent with minimum expenditure of power (see p. 86). In the case of voltmeters and the pressure windings of wattmeters the resistance or impedance should therefore be a maximum, while in that of ammeters and the current coils of wattmeters, etc., it should be a minimum.

It thus becomes a matter of compromise, and for each pattern of instrument a particular number of **ampere-turns** is found from experience to give the best results. The following figures may be taken as a guide to modern practice, in the case of switchboard instruments of ordinary size :—

Type of Instrument.	Ampere-Turns.
Moving iron ammeter or voltmeter . .	300 to 500
Moving coil ,, ,, . . .	0·3 to 1
Induction ,, ,, . . .	300 to 500
Dynamometer ,, ,, moving coil	10 to 20
,, ,, ,, fixed ,, .	500 to 1,000
,, wattmeter pressure coil . . .	20 to 40
,, ,, current coil . . .	500 to 1,000

In the case of dynamometer instruments it must be remembered that the torque depends upon the product of the ampere turns in the fixed and moving windings.

Having decided upon the number of ampere-turns, the **best winding** must be calculated. One of the simplest cases is that of a moving iron ammeter. A size of wire, strip, or cable having been selected (allowing a current density of some 1,300 amperes per square inch, or 2 amperes per square millimetre) and the required number of turns calculated, the necessary winding space is then known, and with it the size of bobbin. It is well to check the result by working out the watts dissipated in heat compared with the cooling surface. About 0·1 watt per square centimetre of external surface will be satisfactory.

In **calculating the space required for a winding,** allowance must be made for the thickness of the covering, and the table on p. 71[1] will be found useful in this connection :—

As an example of the use of this table it will be seen that a wire 1 mm. in diameter has a cross-sectional area of 0·785 sq. mm. and, if double silk-covered, occupies a winding space of 1·010 sq. mm., so that 1,000 turns would require a space of 1010 sq. mm., or, say, 5 cms. long by 2 cm. deep. In calculating the space occupied, allowance has been made in the table for the turns of each succeeding layer lying, to some extent, in the interstices of the one below it, and average figures for thickness of covering have been adopted.

In the case of a voltmeter bobbin it is essential, in order to keep the temperature coefficient within the required limits, to connect a " swamping " or " idle " resistance in series with the copper winding, so that the voltage (E) across the latter is only a fraction of that across the terminals of the instrument. The area of the conductor (a in the table) is given by the expression—

$$a = \frac{l \times N \times s}{1{,}000\ E} \quad . \quad . \quad . \quad . \quad (1),$$

where l is the mean length of a turn, N the ampere-turns,

[1] G. Meyer, *E.T.Z.*, Vol. 36, p. 2 (1915); also W. W. Laebe, *E.T.Z.*, Vol. 36, p. 437 (1915).

Diameter of Bare Conductor (in millimetres).	(a) Cross Section of Conductor (in square millimetres).	(A) Cross-sectional Area occupied per Turn (in square millimetres).		
		Enamel.	D. S. C.	D. C. C.
0·07	0·00385	0·00671	0·0170	—
0·08	0·00503	0·00832	0·0195	—
0·10	0·00785	0·01245	0·0250	—
0·12	0·0113	0·01695	0·0312	—
0·15	0·0177	0·0250	0·0419	0·106
0·18	0·0255	0·0346	0·0540	0·139
0·20	0·0314	0·0418	0·0632	0·175
0·22	0·0380	0·0498	0·0727	0·191
0·25	0·0491	0·0630	0·0886	0·216
0·30	0·0707	0·0886	0·1183	0·262
0·35	0·0962	0·1195	0·1525	0·311
0·40	0·126	0·154	0·191	0·425
0·45	0·159	0·192	0·234	0·486
0·50	0·196	0·236	0·282	0·555
0·55	0·238	0·283	0·333	0·624
0·60	0·283	0·334	0·389	0·700
0·65	0·332	0·393	0·448	0·781
0·70	0·385	0·453	0·513	0·900
0·80	0·503	0·588	0·671	1·085
0·90	0·636	0·741	0·831	1·285
1·00	0·785	0·913	1·010	1·699
1·10	0·950	1·098	1·245	1·95
1·20	1·131	1·301	1·461	2·21
1·30	1·327	1·528	1·695	2·50
1·40	1·539	1·77	1·945	2·80
1·50	1·767	2·03	2·22	3·125
1·60	2·011	2·30	2·50	3·46
1·70	2·270	2·60	2·80	3·82
1·80	2·545	—	3·13	4·18
1·90	2·835	—	3·46	4·58
2·0	3·142	—	3·82	4·99
2·1	3·464	—	4·18	5·42
2·2	3·801	—	4·58	5·84
2·3	4·155	—	4·98	6·30
2·4	4·524	—	5·40	6·78
2·5	4·909	—	5·85	7·28
2·6	5·31	—	6·30	7·78
2·7	5·73	—	6·78	8·31
2·8	6·16	—	7·27	8·86
2·9	6·61	—	7·78	9·42
3·0	7·07	—	8·32	10·62

and s the resistance of 1 metre of the material used for the winding, of 1 sq. mm. in area.[1]

Having determined a (and therefore A from the table), the cross-sectional area of the winding can be found thus :—

$$\text{Cross section of winding} = A \frac{N}{ia} \quad . \quad . \quad (2),$$

where i is the allowable current density from considerations of heating (say 2 to 3 amperes per square millimetre). The current taken by the instrument is $i \times a$, and if this is considered excessive a must be reduced (*i.e.*, a smaller gauge of wire used), which will have the effect of increasing E (see equation 1) and therefore of reducing the available swamping resistance. It will be seen for equation 2 that, apart from variations in the **space factor** $\frac{A}{a}$, the winding space required is independent of the size of wire used, so that for constant ampere-turns the size of bobbin required will be the same for all current ranges.

The **watts dissipated in heat** can be shown, from equation 1, to be—

$$\text{Watts} = \frac{N^2 \times l \times s}{1{,}000 \times \text{cross section of winding}} \times \frac{A}{a}.$$

From this it will be seen that the watts dissipated in heat are independent of the current so long as the ampere-turns remain constant, and also the ratio $\frac{A}{a}$.

The most common problem met with is the determination of the **best winding for a given size of bobbin**, and for this purpose a certain amount of "trial and error" is usually entailed.

The **following relations hold good,** neglecting variations in the ratio $\frac{A}{a}$:—

[1] For copper $s = 0{\cdot}0168$.

In any coil—

Number of turns varies as $\frac{1}{a}$;

Resistance varies as $\frac{1}{a^2}$;

" " (turns)^2.

In an ammeter coil—

Ampere-turns (with a given current) vary as $\frac{1}{a}$;

Voltage drop[1] (with a given current) varies as $\frac{1}{a^2}$;

Current (to give a certain number of ampere-turns) varies as a;

Voltage drop[1] (for a given number of ampere-turns) varies as $\frac{1}{a}$;

Voltage drop (for a given number of ampere-turns) varies as number of turns;

Voltage drop (for a given number of ampere-turns) varies as $\frac{1}{\text{current}}$.

Consequently the watt loss is constant.

In a voltmeter or other pressure coil—

Ampere-turns (for a given voltage drop) vary as a;
Current taken (for a given voltage drop) varies as a^2;
Watt loss (for a given voltage drop) varies as a^2.

In the case of pivoted or suspended coils the problem is further complicated by considerations of weight and the resistance of the leading in strips or springs.

The question of **weight** is usually settled once and for all by the design, since, whether the coil is wound with fine or coarse wire, the total weight will not vary much. The **resistance of the leading in springs** or strips can be

[1] This applies to reactance as well as to ohmic drop (see p. 74).

neglected in the case of voltmeters and pressure windings generally, but is of considerable importance with drop voltmeters used as ammeters. In these, as larger and larger wire is used, the drop across the winding falls off in proportion to $\frac{1}{a}$, but, the resistance of the leading in strips or springs remaining constant, a minimum drop is reached when the resistance of the winding is equal to that of the springs. If a is still further increased the drop becomes greater owing to the larger drop over the springs (see p. 33).

It frequently happens that, owing to the restricted winding depth in moving coils, the most suitable size of wire cannot be used in one or more layers, and for this reason it is sometimes necessary to wind in two or even three parallels. For the same purpose wire of rectangular section may be used to advantage (see also p. 150).

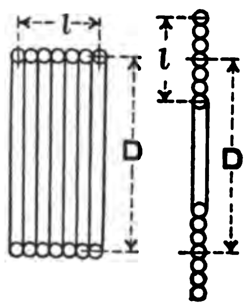


FIG. 35.—Calculation of Self-induction of Coil.

In calculating **windings for alternating current** instruments, self-induction and capacity have to be taken into account as well as ohmic resistance. In any coil having an air core,[1] if the current is kept the same, the self-induced voltage will be nearly proportional to the square of the number of turns. If, on the other hand, the ampere turns are kept constant (as is more usually the case), the self-induced voltage is proportional to the number of turns. It has been seen that the ohmic drop is also proportional to the number of turns; and it, therefore, follows that the angle of lag is constant, and the impedance proportional to the number of turns.

For a discussion of the methods of winding non-inductive resistances see p. 54.

It is very often necessary to predetermine the **self-**

[1] This applies to iron-cored coils also if the ampere turns do not vary widely.

induction of a coil, and this is readily carried out as follows[1] :—

$$L = \frac{\pi^2 D^2 N^2}{l \times 10^6} \times K,$$

where—

L = self-induction in millihenries;
D = mean diameter of coil in centimetres;
N = number of turns;
l = axial length of coil in centimetres;
K = a constant, depending upon the dimensions.

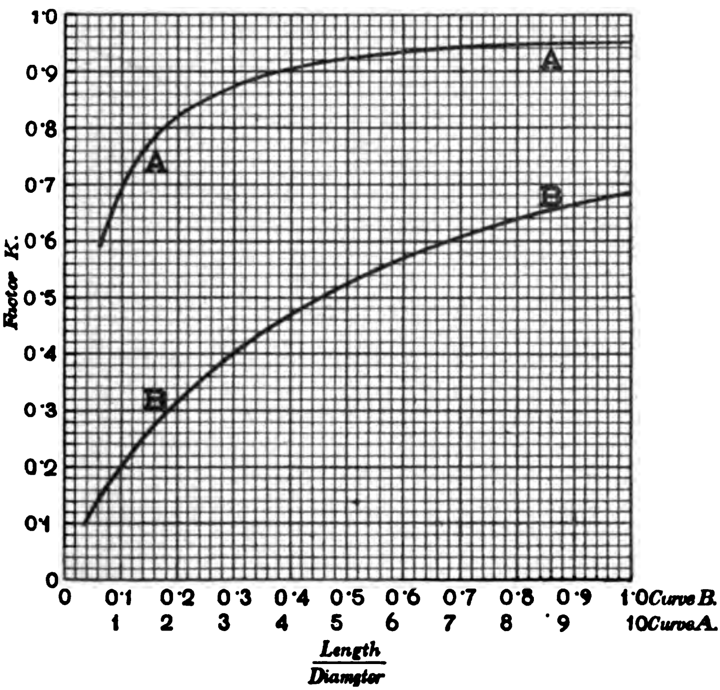


FIG. 36.—Calculation of Self-induction of Coil.

If the coil consists of a single layer, wound in either of the ways shown in Fig. 35, K can be found from the curves of Fig. 36. For example, in the case of a coil of diameter

[1] The method is due to P. R. Coursy (*Electrician*, Vol. 75, p. 841 (1915)).

5 cms. and length 15 cms. wound with 150 turns: $l/D = \frac{15}{5} = 3$, and from curve A; $K = 0{\cdot}87$, so that—

$$L = \frac{\pi^2 \times 5^2 \times 150^2}{15 \times 10^6} \times 0{\cdot}87 = 0{\cdot}32 \text{ millihenries.}$$

If the winding depth is not negligible, a correction (k, Fig. 37), depending upon the dimensions, has to be subtracted from K.

For example, in the case of a coil of 200 turns having

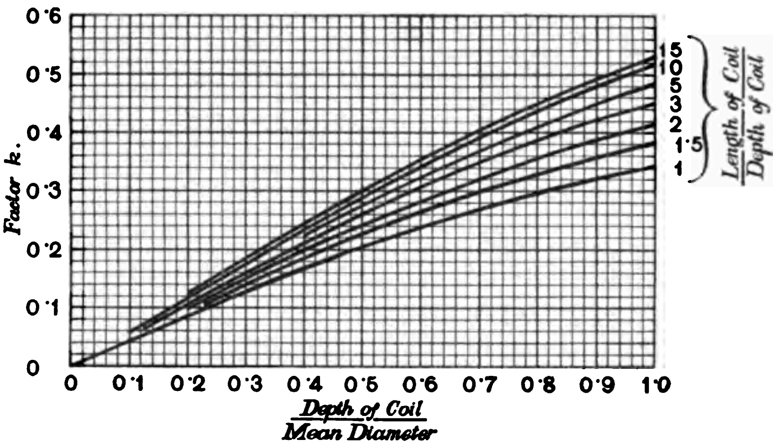


FIG. 37.—Calculation of Self-induction of Coil.

$l = 10$ cms., $D = 5$ cms. winding depth, $d = 2$ cms. Then $l/D = \frac{10}{5} = 2$, and, from Fig. 36, $K = 0{\cdot}82$. $\frac{d}{D} = \frac{2}{5} = 0{\cdot}4$, and $\frac{l}{d} = \frac{10}{2} = 5$, so that, from Fig. 37, $k = 0{\cdot}22$.

Consequently the self-induction is—

$$\frac{\pi^2 \times 5^2 \times 200^2}{10 \times 10^6}(0{\cdot}82 - 0{\cdot}22) = 0{\cdot}59 \text{ millihenries.}$$

In other cases the flux per ampere may be known, and then the self-induction can be calculated from the formula—

$$L = \frac{\Phi}{I} \times \frac{N}{100},$$

where Φ is the total flux and I the current flowing.

Choking Coils.

In a great many alternating current instruments choking coils (often spoken of as impedance or reactance coils) are employed, and as their construction is dealt with in but few text-books, it may be well to go into the question somewhat fully.

When an alternating current is passed through any coil in which it produces a strong magnetic field, the current flowing is determined by the inductance or choking effect of the coil, as well as by its resistance. **Inductance**[1] may be defined as the property of a circuit in virtue of which it opposes any change of current. The unit is known as the henry and is such that an E.M.F. of 1 volt is induced by a change of current at the rate of 1 ampere per second. If the current is growing, this E.M.F. tends to retard its growth ; if dying away, it tends to maintain it.

It will be found that the current lags behind the potential difference at the terminals of the coil, this lag reaching its maximum value, of a quarter of a cycle (90°), when the resistance of the coil is negligible compared with its inductance. It is impossible to construct a coil which is entirely inductive, *i.e.*, possesses no resistance, but it is easy to design one whose characteristics closely approach those of a pure inductance. Such a coil is spoken of as a **choking coil**, and **possesses the following features** :—

The magnitude of the alternating current in it depends directly on the applied voltage and inversely on the inductance of the coil. It is, also, inversely proportional to the frequency. Thus, if—

L = inductance of coil in henries,
I = current in amperes (R.M.S.),

[1] For a simple method of calculating the self-induction of an ironless coil see p. 75.

E = applied voltage (R.M.S.),
f = frequency in cycles per second,

then $$I = \frac{E}{2\,\pi f L}.$$

The current lags 90°, or a quarter-cycle, behind the E.M.F.

Should the coil have an appreciable resistance (R ohms), both the current and angle of lag will be modified, and in this case—

$$I = \frac{E}{\sqrt{(2\,\pi f L)^2 + R^2}},$$

while if φ is the angle by which the current lags behind the voltage—

$$Cos\ \varphi = \frac{R}{\sqrt{(2\,\pi f L)^2 + R^2}}.$$

From these expressions the phase displacement and current may be calculated if the inductance, resistance, and frequency are known.

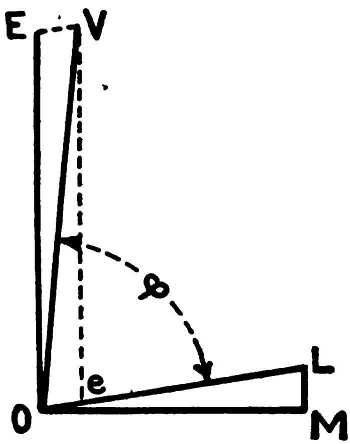


FIG. 38.—Choking Coil Vector Diagram.

The formulæ are only strictly true for choking coils in which there is no iron or other metal in the magnetic circuit. In practice, iron is invariably used, on account of the very considerable saving both in dimensions and in copper. The result of the use of iron in the circuit may, perhaps, be best explained by reference to a diagram (Fig. 38). In this case—

OE represents the E.M.F. set up in the coil windings ;

OM is the corresponding magnetising current, and is equal to $\frac{OE}{2\,\pi f L}$;

ML represents the component of the whole current required to balance the iron losses due to hysteresis and eddy currents, and is equal to $\frac{\text{iron loss in watts}}{OE}$;

OL then represents the total current passing;

Oe (in phase with *OL* and to the same scale as *OE*) represents the voltage drop due to the ohmic resistance of the coil.

Then, setting up *eV* parallel and equal to *OE*, we get—

OV = applied voltage as measured at the coil terminals;
φ = angle of lag of current behind P.D.

At first sight, it would appear that the use of iron must decrease the angle of lag in a choking coil, since the losses in the iron reduce the lag by the angle *LOM*. It should be remembered, however, that the iron reduces the number of turns required and consequently gives a lower resistance and smaller *Oe*, so that the angle *VOE* is reduced. It may be assumed that **for the maximum angle of lag** (φ) the combined iron and copper losses should be as small as possible, and that this is generally secured by making them equal to one another.

The use of metal supporting frames for choking coils, whether iron-cored or otherwise, is undesirable, since these are a source of eddy currents which both reduce the choking effect and decrease the phase angle. There is no practical objection to the use of metal, however, if due precautions are taken to ensure that there are no circuits completely enclosing the flux. When extra precautions are necessary the frame may be composed of a high resistance alloy.

Sometimes, choking coils are designed merely **to absorb a given voltage** at some stated current and frequency, in which case the iron and copper losses may both be very much greater and are, in fact, only limited by the allowable temperature rise of the coil.

A compact and efficient form of **choking coil for small currents** is shown in Fig. 39. The core is made up of

laminated iron stampings, but two short air-gaps are introduced. Without these the flux density in the iron would be excessive, and considerably increased iron losses would result. On the other hand, if the iron core was removed, making the magnetic circuit entirely through air, considerably increased resistance losses would be entailed. The design shown, moreover, lends itself well to instrument work, since the inductance can be varied over a convenient range by adjusting the length of air-gap.

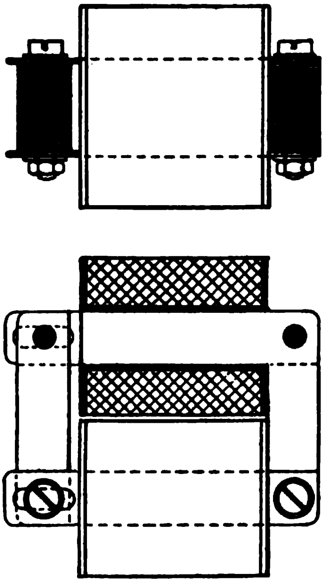


FIG. 39.—Small Choking Coil.

The following method of **calculating a choking coil** of this pattern is due to L. Murphy :—

Let A be the area of the path at the air-gap, in square centimetres ;

Let l = the length of the air-gap, in centimetres ;
E = the induced voltage (R.M.S. value) ;
I = current, in amperes (R.M.S. value) ;
N = the number of turns ;
B = the flux density, in c.g.s. lines per square centimetre (maximum) ;
Φ = the total magnetic flux (maximum) ;
f = the frequency in periods per second.

Then $E = 4{\cdot}44 \times \Phi \times N \times f \times 10^{-8}$,

and $\Phi = B \times A = \frac{4\pi}{10} \times \frac{\sqrt{2}I..N}{l \times 1{\cdot}1} \times A.$

If it is assumed that 10 per cent. of the total magnetising force is required to overcome the reluctance of the iron, it follows from the above equations that—

$$N = 3{,}750\sqrt{\frac{E \times l}{I \times A \times f}},$$

$$E \times I = 2{\cdot}75 \times B^2 \times A \times l \times f \times 10^{-8},$$

$$\text{or} \quad A \times l = \frac{E \times I \times 10^{-8}}{2{\cdot}75 \times B^2 \times f}.$$

In instrument work the maximum possible phase angle is usually required, and, to this end, the iron used must be such that the losses due to hysteresis and eddy currents are a minimum. Assuming the use of stalloy iron 0·5 mm. thick, the best flux density will be 7,000 to 11,000 (maximum) at a frequency of 25 cycles, or 6,000 to 10,000 at a frequency of 50 cycles per second. Now, from the last equation it will be seen that when once the flux density and frequency have been fixed the volt ampere load capacity of the choker depends only upon the cubic contents of the air-gap, so that it is possible to vary the design considerably by using a long gap of small area or a short gap of large area.

This question is mainly settled by considerations of cost and compactness; a choker with a very long gap will require an excessive number of turns, and the iron path may have to be made abnormally long in order to accommodate the winding. On the other hand, an unduly short gap means an extravagant iron section and each turn of the winding correspondingly lengthened. It will thus be seen that, in order to arrive at the best result, it may be necessary to make several approximations, but it may be stated as a guide that the best air-gap length will not exceed 2 mms. for capacities up to 100 volt amperes.

An example may make the matter clearer. Let it be assumed that a choking coil is required to drop 60 volts at a frequency of 25 cycles per second with 0·12 ampere flowing.

As a first approximation, let B be taken as 7,500.

$$A \times l = \frac{60 \times 0{\cdot}12 \times 10^{-8}}{2{\cdot}75 \times 7{,}500 \times 25} = 0{\cdot}185 \text{ cu. cm.}$$

If l is 1 mm., we have

$$A = 1{\cdot}85 \text{ sq. cm.},$$

and therefore

$$N = 3{,}750\sqrt{\frac{60 \times 0{\cdot}1}{0{\cdot}12 \times 1{\cdot}85 \times 25}} = 3{,}900 \text{ turns approximately},$$

and the ampere-turns $= 3{,}900 \times 0{\cdot}12 = 468$.

For the choker shown in Fig. 39 the ratio of depth of winding to length of coil would be about 1 to 3, and assuming a current density of 100 ampere-turns per square centimetre of winding section, each coil might have a length of approximately 2·7 cms. and a depth of 0·9 cm. Hence the total length of iron path will be about 16 cms., and the volume of the core about 39 cub. cms. The iron loss in stalloy, for $B = 7{,}500$ and 25 cycles is 0·008 watt per cubic centimetre, so that the total iron loss, in this case, will be 0·3 watt. Assuming that the wire is either single silk-covered or enamelled, the winding space factor may be taken, for a first approximation, as 0·4, while the length of a mean turn will be about 5 cms. Hence the copper loss[1] will be—

$$\frac{(0{\cdot}12 \times 3{,}900)^2 \times 5}{2{\cdot}42 \times 0{\cdot}4} \times 2 \times 10^{-6}$$
$$= 2{\cdot}27 \text{ watts.}$$

This design could therefore be greatly improved by making copper and iron losses more nearly equal, which could be done by increasing either the section of the iron or the flux density at which it is worked. If the former course is adopted, there will be an increase in iron loss proportional to the increased section, while the air-gap will be proportionately shorter. On the other hand, if the winding space remains the same, the copper loss will be reduced in proportion to the square root of the increase of air-gap area. Thus, if the sectional area of the core is doubled, the iron loss will become

[1] Copper loss in any coil $= \dfrac{(\text{Ampere-turns})^2 \times \text{length mean turn} \times \text{specific resistance of material}}{\text{Section of winding space} \times \text{space factor}}$.
The specific resistance of copper is nearly 2 microhms per centimetre cube at 60° C., which is a conservative estimate for the working temperature.

0·6 watt, and the copper loss 1·6, which is only a slight improvement in the total watts.

If the second course is followed, and the flux density is increased, the iron loss will increase approximately as the square of the flux density. At the same time, the gap length must be reduced in proportion to the square of the increased density, and the copper loss will also be reduced in the same ratio. Therefore, by increasing the flux density to $7{,}500 \times \sqrt{2} = 10{,}600$, the iron loss again becomes approximately 0·6 watt, but the copper loss is reduced to 1·13 watt, so that there is a considerable improvement both in watt loss and in weight of material. In practice the iron loss invariably exceeds the calculated value, so that it is wise to make the copper loss slightly the greater when designing.

In this case there is no doubt that the size would be ample from a heating point of view, but it is always well to check this, allowing a maximum of 0·05 watt per square centimetre for the whole of the exposed surface, including core and coil.

The power factor of such a coil will be—

$$\frac{\text{Watt loss}}{\text{Volt amperes}} = \frac{1{\cdot}13 + 0{\cdot}6}{60 \times 0{\cdot}12} = 0{\cdot}24,$$

so that the effective angle of lag is 71°, and from this it will be seen that it is somewhat difficult to design a small choking coil for a phase displacement approaching 90°, this difficulty becoming greater the lower the frequency. In the example given some further advantage might have been gained by raising the flux density to an even higher value, but it must be remembered that with over-saturation the wave form of the current may be seriously affected (see p. 84).

If the coil has an **open magnetic circuit** (Fig. 40), the air-gap ampere-turns cannot be calculated by the formula just given, since the length is indefinite. Evershed has, however, given an approximate empirical formula applicable to such cases. It is as follows :—

$$\text{Air-gap ampere-turns (R.M.S.)} = \frac{\text{flux (R.M.S.)}}{8\sqrt{A}},$$

where A is the sum of the superficial areas of the two exposed

ends of the iron core (in square inches). From this formula it will be seen that the efficiency of the choker depends largely upon the projection of the core beyond the ends of the winding. This should not be less than 20 per cent. of the length of the core. The length of the coil is unimportant, and is determined mainly by considerations of winding space and heating.

FIG. 40.—Open Magnetic Circuit Choking Coil.

If a wide range of adjustment is required a coil on the lines of Fig. 40 will be found best, the core projecting 25 per cent. of the coil length at each end. Moreover, the longer the coil and the smaller the central hole, the wider will be the range of adjustment obtainable by partially withdrawing the core.

From what has been said, it will be clear that the current taken by a choking coil depends upon the induced flux—that is, upon the permeability of the iron. But this, in its turn, falls off as the flux density increases, so that during each cycle, as the applied pressure rises, the self-induction falls, and the current, therefore, increases at a more rapid rate than the pressure. The result is that the wave form of the **current does not correspond with that of**

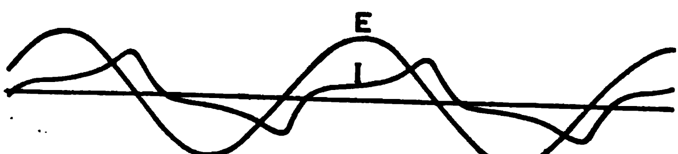


FIG. 41.—Distortion in a Choking Coil.

the pressure applied to the terminals of the coil. This is well shown in Fig. 41[1], where E represents the sinusoidal applied pressure and I the current flowing. Modern brands of transformer iron (silicon alloys, *e.g.*, stalloy) which have low iron losses permit of higher flux densities, and conse-

[1] From a paper by F. T. Chapman, *Faraday House Journal*, 1915, p. 43.

quently lead to increased distortion,[1] which can only be guarded against by keeping on the lower part of the magnetisation curve (p. 56).

It should be observed that, although the magnetising current is distorted, the wave of magnetic flux closely follows that of the impressed voltage. As a result, distortion does not occur between the primary and secondary of current or pressure transformers under ordinary conditions.

In special cases, however, distortion may occur. For example, an inspection of Fig. 41 shows that there is a considerable **triple harmonic** in the magnetising current wave (I); and since a triple harmonic current cannot flow in the case of three transformers connected in star, it follows that the flux cannot be sinusoidal under these conditions, and a distorted secondary E.M.F. must result. On the other hand, if the secondaries are delta-connected, a compensating triple frequency current circulates round the delta, and an undistorted secondary E.M.F. is produced.

Condensers.

The use of condensers with alternating current instruments is mainly in connection with certain types of phase-meter and frequency meter, and as a means of isolating from the mains or extending the range of high tension electrostatic voltmeters. Condensers for the last-mentioned purpose are described on p. 190.

The characteristics of capacity are in many respects analogous, although opposite, to those of inductance. The current passing into a perfect condenser is 90° out of phase with the applied pressure, but in this instance the current leads instead of lagging. The **current passing** is directly proportional to the frequency. If C represents the capacity in microfarads,[2] then $I = \dfrac{2\pi f C E}{10^6}$, where I is the current

[1] See Hague and Neville, *Electrician*, Vol. 78, p. 44 (1916).

[2] The unit of capacity is the farad, and is the capacity of a condenser such that when a steady pressure of 1 volt is applied to its terminals the amount of electricity stored is 1 coulomb. The practical unit is one-millionth of this, and is known as the microfarad.

flowing, E the imposed voltage, and f the frequency per second.

This expression is only true if the E.M.F. is strictly sinusoidal. The presence of any ripples of higher frequency will greatly increase the R.M.S. value of the current taken. To calculate the capacity required, when the current, voltage, and frequency are known, the above expression may be stated thus :—

$$C = \frac{I \times 10^6}{2\,\pi f E} \text{ microfarads.}$$

It may be useful to remember, from this equation, that 32 microfarads are required per ampere at 100 volts and a frequency of 50 cycles per second.

Paper condensers have now been brought to a high state of perfection. The losses due to leakage and dielectric hysteresis are so small as to be quite negligible, for most purposes. Chance of breakdown has been reduced to a minimum by excluding all moisture from the paper used as the dielectric by drying it *in vacuo* and afterwards impregnating it with oil or paraffin wax. Of even greater importance than the care bestowed[1] upon the dielectric, however, is the invention of Mansbridge whereby condensers are made self-sealing. No tinfoil is used, as formerly, in the construction, but the surface of the paper is covered with an extremely thin coating of electrically deposited tin. If a breakdown should occur, the spark volatilises the metal coating around the puncture and thus automatically interrupts the fault. Such condensers may be used with just as much confidence as a resistance or a choking coil.

Expenditure of Power.

It is often assumed that the instrument with the lowest consumption of power is necessarily the best ; but this does not, by any means, follow. The chief difficulty with which the designer of electrical measuring instruments has to contend is the smallness of the working forces available. For most purposes, in fact, the skill of the designer shows itself

[1] For a recent description see *Electrician*, 1918, p. 530.

rather in increasing the torque per gramme weight of moving parts than in reducing the watts expended. In the case of a central station voltmeter, for example, it is immaterial whether the power consumed is 4 watts or 16 watts, the important question being whether the heat generated is effectively disposed of without errors due to self-heating and, above all, whether the torque is adequate. In some circumstances, on the other hand, minimum power consumption is of importance, owing to its effect upon the precision of the measurement. Such a case arises when a number of instruments are to be operated from a common current transformer, or when the power expended in the instrument bears a large proportion to that which is to be determined (*e.g.*, in the measurement of the iron losses of a small transformer.

The table on p. 88 will serve as a guide to the probable expenditure of power in modern instruments of the types enumerated. The figures assume instruments suitable for a full scale current of 10 or 20 amperes, a voltage of 100 or 200 volts, and. in the case of alternating currents, a frequency of about 50 periods. At the same time, the latitude allowed will in the majority of instances cover any variation in consumption due to the range. In some instruments, for example the moving iron, the power expended is almost independent of range or frequency. Others, such as the induction pattern, are less efficient at low frequencies. In the moving coil and hot wire varieties, amongst others, the watts expended are directly proportional to the range of current or pressure. In the case of resonance frequency meters it is extremely difficult to give reliable figures, as so much depends not only upon the voltage and normal frequency, but also upon the ratio of the maximum to the minimum frequencies to be measured. The higher this ratio, the larger will be the consumption of power.

The figures for relays and switch trip-coils have been added as being of use in determining the necessary output of current and potential transformers when, as is often the case, they are called upon to operate switchgear in addition to measuring instruments.

Expenditure of Power for Full Scale Deflection of Switchboard Instruments.

Type of Instrument.	Volt Ampere Consumption.	
	Current Winding.	Pressure Winding.
Moving Iron:		
Ammeter, 6 ins. or 8 ins. round	2 to 4	—
Large sector or edgewise .	4 to 8	—
Voltmeter, 6 ins. or 8 ins. round	—	5 to 10
Large sector or edgewise .	—	10 to 20
Moving Coil:		
Ammeter, all sizes . .	Amperes × 0·05 to 0·1	—
Voltmeter, ,, . . .	—	Volts × 0·01 to 0·03
Hot Wire:		
Ammeter, 6 ins. or 8 ins. round	Amperes × 0·2 to 0·4	—
Voltmeter, ,, ,, ,,	—	Volts × 0·1 to 0·2
Induction:		
Ammeter, 6 ins. to 8 ins. round	3 to 7	—
Voltmeter, ,, ,, ,,	—	10 to 20
Wattmeter, ,, ,, ,,	2 to 4	5 to 8
Watt-hour meter switchboard	1·5 to 3	3 to 8
Dynamometer:		
Ammeter, 6 ins. or 8 ins. round	Amperes × 0·4 to 1·5	—
Voltmeter, ,, ,, ,,	—	Volts × 0·05 to 0·1
Wattmeter, ,, ,, ,,	4 to 6	Volts × 0·01 to 0·05
Phase Meter, 6 ins. or 8 ins. round	5 to 10	Volts × 0·05 to 0·1
Frequency Meter (Resonance)	—	2 to 15
Graphic Ammeter:		
Moving coil	Amperes × 0·1 to 0·2	—
Moving iron . . .	4 to 8	—
Dynamometer . . .	Amperes × 1 to 2	—
Graphic Voltmeter:		
Moving coil	—	Volts × 0·02 to 0·06
Moving iron . . .	—	10 to 20
Dynamometer . . .	—	Volts × 0·05 to 0·1
Wattmeter dynamometer .	5 to 10	Volts × 0·05 to 0·1
Relays:		
Overload solenoid . .	15 to 30	—
,, induction . .	10 to 20	—
Reverse solenoid . . .	10 to 20	10 to 20
,, dynamometer . .	8 to 15	8 to 15
Circuit-breaker:		
Current coil. . . .	20 to 40	—
Volt ,, . . .	—	20 to 40

It will be noticed that the consumption is given in volt amperes and not in watts. This is due to the fact that where they differ appreciably it is usually the volt amperes which

are the determining factor. See, for example, p. 323, where it is shown that the secondary load in volt amperes determines the performance of a current transformer.

As regards the consumption in watts, in the case of the moving iron, hot wire, and dynamometer patterns (including dynamometer phase meters) the pressure circuit watt and volt ampere consumptions are practically identical. With the remaining instruments it may be assumed without serious error that the watts are from half to three-quarters of the volt amperes. This latter applies also to the current windings of the moving iron, induction, and dynamometer patterns.

Permissible Temperature Rise.

The question of temperature rise in an instrument is a difficult one, since it depends upon so many factors. The British Engineering Standards Committee give[1] the following as the temperatures which can be withstood safely by various insulating materials :—

Material.	Maximum Permissible Temperature.	Permissible Temperature Rise (taking surrounding Air as 40° C.).
Cotton, silk, or similar material; in air	95° C.[2]	55° C.
Ditto; oil immersed or impregnated	105° C.[2]	65° C.
Enamelled wire (average)	105° C.	65° C.
Mica, asbestos, etc., compounds[3]	125° C.	85° C.
Mica, porcelain, quartz, etc.	No limits.	
Transformer oil	90° C.	50° C.

Since the temperature of the inner layers of a coil is, neces-

[1] "Standardisation Rules for Electrical Machinery," No. 72 (October, 1915). The "Rules of the American Institute of Electrical Engineers" have adopted similar limits.

[2] Experiments by Schüler (*E.T.Z.*, Vol. 37, p. 535, 1916) go to show that after prolonged heating to these temperatures the tensile strength is reduced to about half its original value.

[3] So long as the "binder" is used for structural purposes only and may be destroyed without impairing the mechanical or insulating properties.

sarily, greater than that measurable at the surface, the latter temperature should be 10° or 20°[1] less than those given in column 2 of the table. In drawing up a specification, the heating must be expressed as a rise in temperature above that of the surrounding air. For this purpose 40° C. is taken[2] as the air temperature, so that the permissible rise will be 40° less than the figures given in column 2 of the table and column 3 gives the temperature rise on this assumption.

The ventilation of an instrument winding is usually poor, owing to the surrounding case, so that the allowable watts per unit of surface area must be correspondingly reduced. Again, many instruments are subject to sudden and sometimes to prolonged overloads of considerable and uncertain magnitude, a circumstance which must be taken into account in the design.

In the case of instruments, transformers, series resistances, etc., it is the insulating materials employed which determine the allowable temperature. With external shunts, however, it is rather a question of limiting the temperature so as not to endanger insulating or inflammable materials in the neighbourhood. Shunts have been known to burn out and so open the circuit, but such cases are extremely rare, and, if well designed, shunts may be said to be almost indestructible.

It is generally held that the maximum temperature of a shunt should not much exceed that of boiling water, and, assuming an air temperature of 20° C., this gives a permissible rise of 80° C. at full load.[3]

Unfortunately, the temperature rise of all instruments, and more particularly of shunts, depends very largely upon the conditions under which they are used. For example, unless the connecting leads are of ample section and the

[1] If the temperature of the winding is calculated from a resistance measurement, an allowance of 10° on this account will be adequate. In the case of instrument windings the depth of which is small, 5° or 10° will probably suffice in all cases, even where the temperature is measured by means of a thermometer on the surface of the winding.

[2] *Loc. cit.*

[3] The British Standard Specification for Electricity Meters (August, 1915) lays down a maximum rise of 60° C., but this is unnecessarily low, and will doubtless be revised.

contact surface good, the heat generated, thereby, may very materially increase the temperature rise. Again, in the case of a shunt, the position of the leaves, whether vertical or horizontal, has a considerable effect upon the cooling, and must be taken into account in determining whether the temperature rise is excessive or not (see also p. 48).

General.

The **materials** used, throughout, should be as **non-hygroscopic** as possible.

The **cases** should close down on a rubber, felt, or asbestos gasket, the latter being used in the case of watertight instruments.

The most scrupulous **cleanliness** is essential both during manufacture and in the event of the case being opened at any time. A few particles of dust may be sufficient, entirely, to derange an instrument. It is useful to enamel all cases white inside, as this enables dirt and dust to be more readily detected.

Materials containing sulphur should be avoided, and more particularly so in the neighbourhood of fine wires, which are rapidly attacked by it. A case in point is the rubber tubing often used to cover connecting wires. Ebonite has been found, particularly under the influence of damp, to have a similar effect, and several forms of adhesive tape are particularly objectionable in this respect. **Iron** should be used as little as possible for the working parts, owing to its liability to rust; for the same reason the pivots should be highly polished, since in that state they are less liable to attack.

Terminals and binding screws, whether internal or external, are the better for a coat of nickel or tin, and instrument parts which cannot be protected (*e.g.*, the clocks of graphic instruments) should be heavily lacquered, particularly if for use in tropical climates.

Most makers **seal** their instrument cases to prevent unauthorised interference. The interior mechanism is always

delicate, and, if accessible, frequently suffers in an attempt to remedy a defect which very probably lies outside the instrument altogether.

The **pointer** is an important part which does not always receive the attention it deserves. When it is remembered that the pointer of a 15-in. edgewise instrument is often 12 ins. in length, it will be clear that extreme rigidity is essential.

As usually constructed, the pointers of the larger switchboard instruments consist of a seamless aluminium tube, rigidly attached by means of a clip to the staff at one end and carrying a spade-shaped "flag" at the other. This often has a hole punched out of its centre in order to lighten it. The flag should have a fine point and, together with as much of the pointer as is exposed, should be blackened to make it as visible as possible at a distance.

The smaller switchboard instruments, often, have flat pointers stamped out of sheet, while for portable instruments either wire or tube is employed, flattened out into a "knife-edge" at the end, to facilitate accurate reading.

Whatever form of pointer is used, great care is essential in fixing it to the staff and also in the adjustment of the flexible end stops, which should always be provided. As pointed out on p. 27, the pointer should be insulated from the staff carrying it.

It happens occasionally, in the case of alternating current instruments, that at a particular frequency the pointer is set in resonant vibration. To obviate this the Weston Company have introduced what they call a "trussed" pointer. This is illustrated in Fig. 42, and consists of a double truss of thin tube. The result is a very rigid pointer of small weight. As

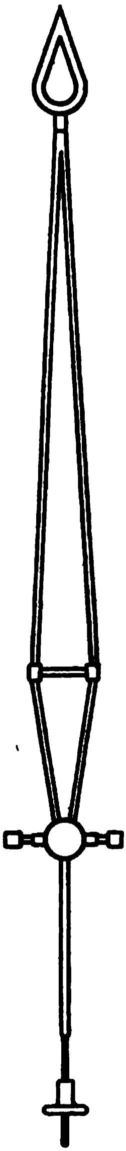


FIG. 42.—Trussed Pointer.

a matter of fact, however, it is easy, by suitably choosing the dimensions of the ordinary tubular pointer, to avoid resonance without the complication of the trussed construction.

Measurement of Resistance and Insulation.

Of the various methods which have been proposed for the measurement of resistance, undoubtedly the most generally useful is that known as the **Wheatstone bridge.** A simple form of this, spoken of as the slide-wire bridge, is shown diagrammatically in Fig. 43. Here X is the resistance to be measured, R a known resistance (preferably of

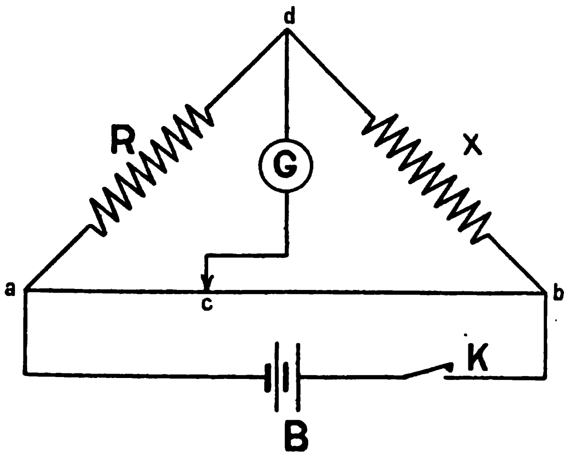


FIG. 43.—Slide-wire Bridge.

about the same value as X), and ab a wire stretched along a scale. The galvanometer G is joined up as shown, and can be connected to the slide-wire at any required point (c). On connecting up the battery B and closing the key K a current flows through acb and adb in parallel. It can be shown that if $\frac{ac}{cb} = \frac{R}{X}$, then the points c and d will be at the same potential, and consequently no current will flow through the galvanometer on closing the galvanometer circuit. The procedure is therefore to slide the contact c up and down the wire ab until balance is obtained, that

is to say until closing the galvanometer circuit produces no deflection. Then

$$X = R\,\frac{cb}{ac}.$$

In order to save calculation, the slide-wire scale can be so graduated that the value $\frac{cb}{ac}$ is read off direct, in which case

$$X = R \times \text{scale reading}.$$

It can be shown that these relations still hold good if the battery and galvanometer are interchanged, that is

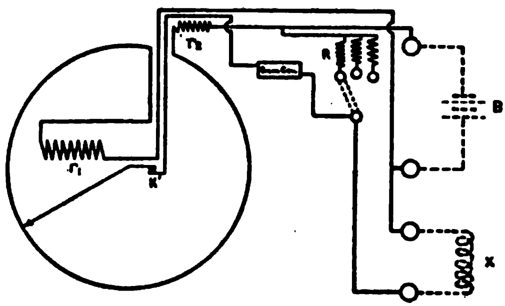


FIG. 44.—"Everight" Ohmmeter.

to say, if the galvanometer is joined between the points *a* and *b* and the battery between *c* and *d*. This arrangement, however, has the disadvantage that an appreciable current flows through the contact-maker, whereas in the other case, when a balance is obtained, no current flows. The best galvanometer to use is one giving maximum sensitiveness at and about zero (see p. 124), and it can be shown that the best galvanometer resistance is—

$$\frac{1}{\frac{1}{R+X}+\frac{1}{ac+cb}}.$$

The sensitiveness and accuracy of the method is greatest when R, X, ac, and cb are all about equal, so that, if R is adjustable it should be varied until the point of balance is nearly in the centre of the slide-wire. If the resistance X is

high it is clearly impossible with a stretched wire to make $ac + cb = R + X$, but a special slide-wire, having any required resistance up to 10,000 ohms, has been introduced by Messrs. Everett, Edgcumbe & Co. for this purpose. It is made by winding a continuous spiral of wire, evenly spaced, on a flat card some 12 ins. long by 4 ins. wide, which is subsequently bent round a circular drum, and held firmly in place. The galvanometer contact (c in Fig. 43) is carried by an arm pivoted concentrically with the drum, and controlled by a milled knob. The knob also carries a pointer moving over a direct reading scale and showing by its position the point on the wire at which contact is being made.

The "**Everight**" **portable ohmmeter** embodies this construction, and the internal connections are shown in Fig. 44. The slide-wire itself only forms the central portion of the arms ac and cb, the remainder of the resistance (r_1 and r_2) being wound on bobbins inside the case. The scale, which is 12 ins. long, is graduated from 10 to 110, and by means of a multiple-way switch (R) any resistance from 0·1 to 11,000 ohms can be measured. When a resistance higher than this has to be dealt with, the instrument is somewhat modified, and can be combined with a self-contained generator giving 200 or 500 volts. The galvanometer, which is of the pivoted D'Arsonval type (see p. 123), is contained in the same case, and is so arranged that the weight of the coil is almost supported by a spring, so that friction is minimised.

When greater accuracy is required than is possible with the slide-wire bridge (*i.e.*, to within less than, say, ½ per cent.) the three arms of the bridge may take the form of resistance coils, mounted either in separate boxes or all fitted into one case. The most usual form is that known as the "**Post-Office**" **pattern** of bridge. The scheme of connections is shown in Fig. 45, the lettering being the same as in Fig. 43, so that the two can be at once compared. The resistances can be varied by short-circuiting, more or less of the coils by means of conical plugs fitting accurately between blocks to which the ends of the various resistance coils are soldered;

ac and *cb* are known as the "ratio arms," and usually consist of three coils each (1,000, 100, and 10 ohms respectively), giving ratios of 100 : 1, 10 : 1, and 1 : 1, as required. The arm R has, generally, a total resistance of something over 11,000 ohms, so that measurements up to 11,000 × 100 = 1,100,000 ohms can be made.

In another form of bridge, known as the **dial pattern,** the

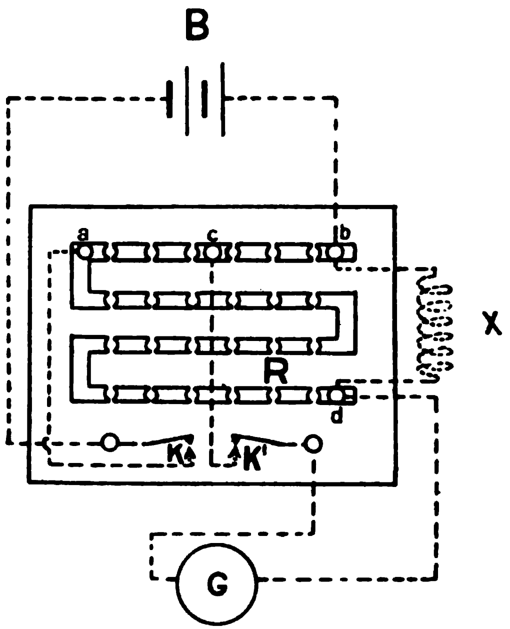


FIG. 45.—"Post-Office" Bridge.

resistance arm R consists of from three to six dials, each having ten coils, more or less of which can be put in circuit by means of a plug. The value of each of the coils in a dial is the same, being, say, 1, 10, 100, and 1,000 ohms respectively. This form is somewhat more convenient to use and to check; it is also more accurate owing to the absence of a large number of plugs in series (with their indefinite contact resistance), but is more bulky.

To avoid the inconvenience of having loose plugs, some

bridges are made with **switch contacts** which, although extremely handy, require great care both in construction and maintenance, if contact errors are to be avoided. When, however, this is taken, they are extremely useful.

The contacts, plugs, etc., of all bridges and resistance boxes should, occasionally, be cleaned with a soft cloth dipped in paraffin. The tops of such boxes are usually of ebonite, and care must be taken not to leave the plugs pressed tightly home when the bridge is out of use, or the ebonite may become permanently distorted, owing to the strain thrown upon it. Ebonite is, also, adversely affected by exposure to sunlight and to even moderately high temperature.

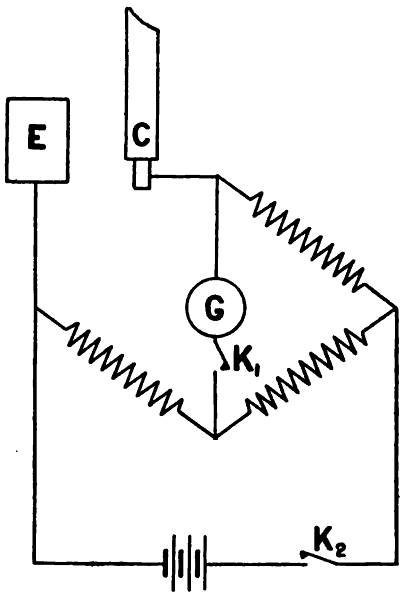


FIG. 46.—Measurement of Insulation of Live Mains.

For some special purposes it is found convenient to operate the **Wheatstone bridge with alternating currents.** To this end, an induction coil (having, usually, a ratio of about 1 : 1) is interposed between the battery and the bridge, while a telephone receiver replaces the galvanometer. By means of such an arrangement the **resistance of electrolytes** can readily be measured. This device is often employed to measure the resistance to **earth of a system of lightning conductors,** since, owing to earth currents and electrolytic E.M.F.'s at the earth-plates, measurements made with a continuous current bridge are unreliable.[1]

The alternating telephone method can be employed for

[1] For other methods of testing earth-plates see p. 383.

all resistance measurements, but is not nearly so sensitive as the continuous current, nor is it so convenient, owing to the fact that the telephone gives no indication as to the direction in which adjustment is required. An absolute cessation of buzzing is, moreover, never attained.

It should be noted that the Wheatstone bridge principle holds good, even when the galvanometer has a permanent deflection, due to an E.M.F. in one or more of the arms. The criterion of balance, in this case, is that the deflection remains unchanged whether the battery circuit is closed or open. In this way it is possible to determine the **insulation resistance of a network while working,** as shown in Fig. 46,

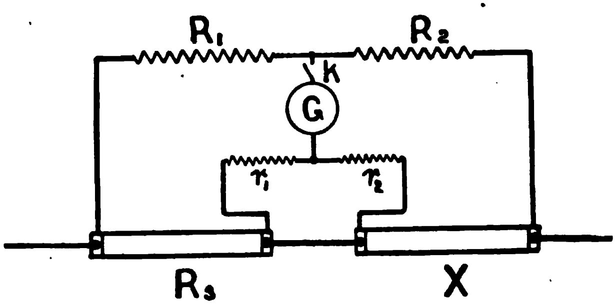


FIG. 47.—Kelvin Bridge.

where C represents one of the live mains, E an earth connection, K_1 and K_2 keys, and G the galvanometer.

Unless special precautions are taken, the Wheatstone bridge is not a suitable instrument for the measurement of **very low resistances,** say less than one-tenth of an ohm, owing chiefly to the difficulty of avoiding contact errors both in the bridge itself and in the wires which are employed to connect it to the resistance to be measured.

Numerous methods are available, such, for example, as the Kelvin bridge, the Carey-Foster bridge, and the differential galvanometer; but although capable of extreme refinement, they have not found much favour with engineers, owing, largely, to the special nature of the apparatus required, and, with the exception of the first named, need not be described here.

The **Kelvin bridge** method is probably the most satisfactory arrangement available where extreme accuracy is required, and when permanently set up is quite as convenient to use as some of the cruder methods. The connections are shown in Fig. 47, from which it may be noted that the method is an extension of the Wheatstone bridge principle, whereby the effect of the contact resistance at the connection between the "known" and "unknown" resistances is eliminated.

The resistances R_1 and R_2 are adjustable and known; R_3 is a standard resistance whose value is of the same order as the unknown resistance X, and preferably of similar current-carrying capacity. The resistances r_1 and r_2 are also adjustable and known. A regulating rheostat and ammeter may be added, in the main circuit, when it is necessary to make the test at some prescribed current. The resistances R_1, R_2, r_1, r_2, should preferably be fairly high, so as to minimise any risk of contact errors in this part of the apparatus, and will usually lie between 100 and 10,000 ohms.

The method of working consists in adjusting these resistances until, on closing K, the galvanometer G shows that a balance has been obtained. But it is essential that the ratio $R_1 : R_2$ should be the same as $r_1 : r_2$, a double adjustment being, therefore, necessary. We then have—

$$\frac{R_1}{R_2} = \frac{r_1}{r_2} = \frac{R_3}{X}.$$

This process of adjustment is somewhat tedious if carried out with separate resistances for each arm, but is greatly simplified if a mechanical interlock is provided between R_1 and r_1 and between R_2 and r_2, so that the condition $\frac{R_1}{R_2} = \frac{r_1}{r_2}$ is automatically maintained. The Kelvin bridge method is just as liable to errors due to thermo-E.M.F.'s as other forms of low resistance measurement, and it is, often, advisable to provide a switch for reversing the main current. It should, also, be noted whether the

galvanometer gives any deflection if its circuit is closed immediately after the main circuit has been opened. If it does, a false zero must be worked to.

In the measurement of low resistances the precaution should always be taken of first clamping together the outer ends of the two connecting wires and measuring their resistance, the value so obtained being subtracted from that subsequently found for the resistance under test.

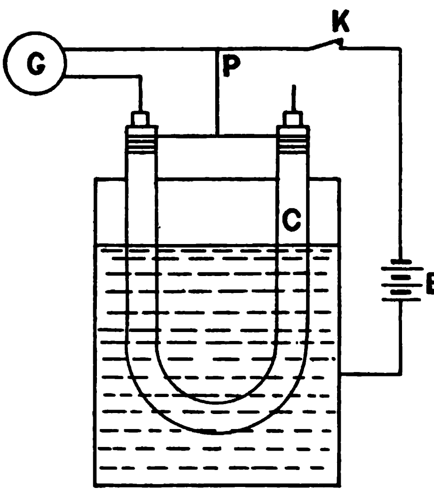


FIG. 48.—Measurement of Insulation by Direct Deflection.

For the measurement of resistances too low to be accurately dealt with by the Wheatstone bridge the potentiometer is undoubtedly the most satisfactory instrument to employ (see p. 111). For a description of the low resistance "ohmmeter" see p. 110.

Commercial measurements of **high resistances** or **insulations** are usually carried out by one of three methods :—

(1) Direct deflection.
(2) Wheatstone bridge.
(3) Deflectional ohmmeter.

Of these the **direct deflection** method is the most universally applicable, and consists in sending a current through the resistance to be measured in series with a galvanometer and noting the deflection. The connections are shown in Fig. 48, where a cable test is taken as an example. The core of the cable is joined to one terminal of a sensitive galvanometer, G, the other being connected to

one pole of a battery, B, the second pole of which is earthed. On closing the key K a current flows in series through the insulation to be measured and the galvanometer, producing a deflection, d_1. If now a known resistance (R) is substituted for the cable, and a second deflection (d_2) obtained, then, assuming the deflections to be proportional to the currents flowing through the galvanometer, the insulation resistance of the cable will be $R \times \frac{d_2}{d_1}$.

It is here assumed that the resistances of the galvanometer and battery are negligibly small compared both with that of the resistance R and of the insulation under test. If this is not the case allowance must be made accordingly. If proportionality between deflection and current cannot be relied upon, d_1 and d_2 should be made approximately equal, either by shunting the galvanometer or by varying the voltage of the battery, due allowance being made for this when calculating the insulation.

It will at once be seen that there is a great chance of surface leakage over the ends of the cable and that, in fact, this leakage might be much greater than that taking place through the insulation itself. The error can, however, be eliminated by the use of what is known as "Price's guard-wire," shown at P. The sheath (if any) is removed for some inches from the end, and a length of bare copper wire is twisted round the insulation between the core and the sheath or "earth." It will be seen from Fig. 48 that with this arrangement any current leaking over the surface of the cable ends will flow through the wire P, and not through the galvanometer, so that inaccuracy due to surface leakage is eliminated.

A short-circuiting key or plug should be provided for the galvanometer, since, if the circuit C has capacity, a comparatively large current rush will take place on closing or opening the key K, and, even if it does not permanently damage the galvanometer, it will very probably cause a change of zero, and should be avoided.

The **Wheatstone bridge method** has already been described

(pp. 93 and 95). The only additional precaution to be taken in this case is to ensure that the insulation of the bridge and its connections is good. As far as possible, in all insulation tests the connecting wires should be stretched in mid-air and not allowed to rest upon the table or ground. A guard-wire can be employed in this case also, its free end being connected to the other pole of the battery.

Whilst for the measurement of insulation in the laboratory either of the methods just described gives good results, it is of the utmost importance for the engineer to be able to make such measurements with rapidity and fair accuracy and without such comparatively complicated and delicate apparatus.

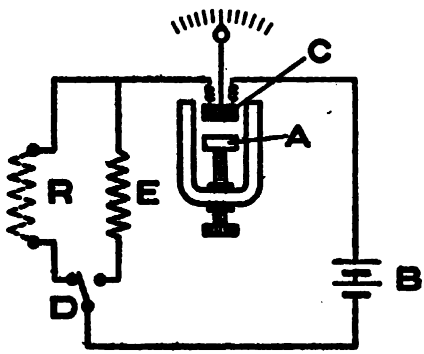


FIG. 49.—Simple Resistance Meter.

The simplest form of instrument for this purpose consists of a moving coil **ammeter** which at a known voltage can be **scaled direct in ohms.** Unless special precautions are taken, the scale is very uneven, since the current flowing is inversely proportional to the resistance. This can be overcome to a certain extent by shaping the pole pieces in an appropriate manner, but another disadvantage lies in the effect on the readings of changes in the voltage of the battery. To compensate for this, the permanent magnet of the ammeter can be provided with an adjustable magnetic shunt by means of which the sensitiveness can be varied. In Fig. 49 the battery B sends a current through the moving coil C and the resistance under test *R*. If the voltage is correct, the value of *R* can be read upon the direct reading scale. In order to check the voltage, the key D is moved to the right, whereby the resistance *E* is thrown into the circuit in place of *R*. If the voltage is normal, the pointer

will then come to rest at a certain point on the scale, usually indicated by a red mark. If it does not, the voltage is too high or too low, and the reading must be corrected accordingly by raising or lowering the magnetic shunt A. When this has been done the indications will be correct for all values of *R* so long as the voltage remains steady.

Such instruments are used to some extent on the Continent; but in this country they have given place to those working on what is known as the "**ohmmeter**" principle, in which the readings are independent of the voltage. The best known are the "Megger" (Evershed and Vignoles), the "Metrohm" (Everett-Edgcumbe), the "Omega" (Paul),

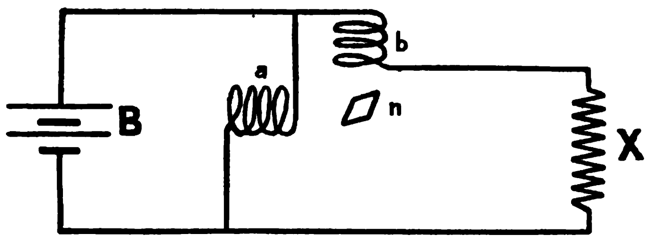


FIG. 50.—Ohmmeter Principle.

and, working on a somewhat different principle, the "Ohmer" (Nalder).

The Evershed set, which has undergone considerable improvement since its first introduction, some twenty years ago, is based on what is often spoken of as the "ohmmeter" principle. The simplest form is shown diagrammatically in Fig. 50. Assuming the battery B to give constant voltage, the force exerted on the needle *n* by the coil *a* will be constant, whereas that due to coil *b* will depend upon the value of the resistance *X*. If the needle *n* is pivoted and carries a pointer moving over a scale, this latter can be so graduated as to read direct in ohms. A little consideration will show, moreover, that the position taken up by the needle will be independent of the voltage of the battery, since any increase or decrease in this will affect the currents in the coils *a* and *b* equally.

The earlier Evershed ohmmeters were constructed on this principle, the only important modification being that the needle *n* was strengthened by being magnetised by a coil connected in series with *a*. The disadvantages of such an instrument were that it was much affected by stray magnetic fields and that the working forces were extremely small, while the weight of the moving magnet was considerable.

Many years ago an ohmmeter was constructed by Carpentier in which the magnet was fixed and the windings movable.

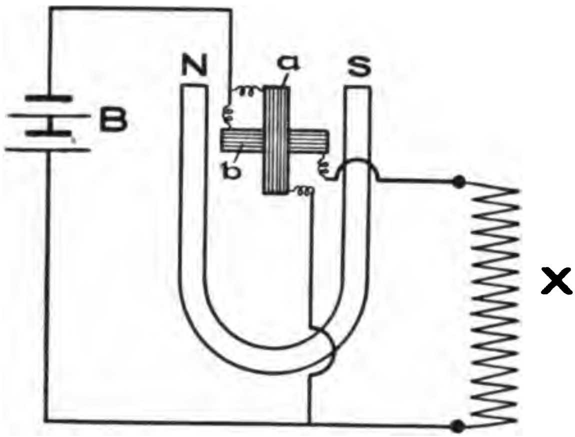


FIG. 51.—Early Moving Coil Ohmmeter.

Fig. 51 shows the arrangement, the respective coils being lettered similarly to Fig. 50. The difference between the two arrangements is that the coils *a* and *b* are, in the present case, fixed at right angles to one another and attached to a pivoted spindle carrying the pointer. The principle of action is exactly the same as that of the instrument just described, the resultant field due to *a* and *b* setting itself parallel to the flux due to the magnet N S. A disadvantage of this arrangement lies in the long air-gap, which results in a very weak field, with consequent loss of control and susceptibility to disturbance by stray fields, and also in the cramped scale which it gives. To overcome these disadvantages Harris has developed an ohmmeter, known as the "**Omega,**" in

which the crossed coil principle is retained, but pole pieces and a core are added. Such an arrangement gives a narrow gap, and consequently a radial field, so that, unless special precautions are taken, the instrument is unstable and if once disturbed will fly to the end of the scale. Harris overcomes this by using a very wide coil, which as it rotates comes more and more out of the magnetic field and so finds a position of stable equilibrium for all values of X.

The latest pattern of Evershed ohmmeter, known as the "**Megger,**" is also based on the moving coil principle, but differs in detail. Two coils, which may be called the pressure

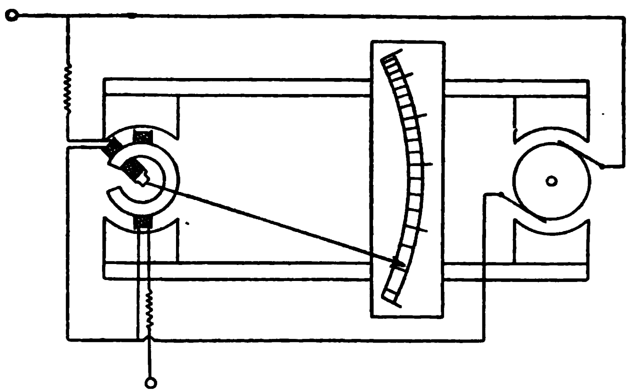


FIG. 52.—The "Megger."

and current coils, respectively, are employed (corresponding to a and b in Fig. 50); but, instead of these being fixed, and the magnet pivoted, the coils are pivoted and the magnet fixed as in the Carpentier instrument (Fig. 51). The principle of action is shown diagrammatically in Fig. 52, from which it will be seen that the current coil resembles that of an ordinary moving coil instrument except that the core is annular. The pressure coil threads on this annular core, so that when the pointer is at infinity on the scale the pressure coil is in a very weak field and experiences no torque. When at zero, on the other hand, it is under the pole, and the field is comparatively strong. As a result the moving system finds a stable position for every value of

external resistance from zero to infinity, and, moreover, the scale is very open at the lower end and close at the

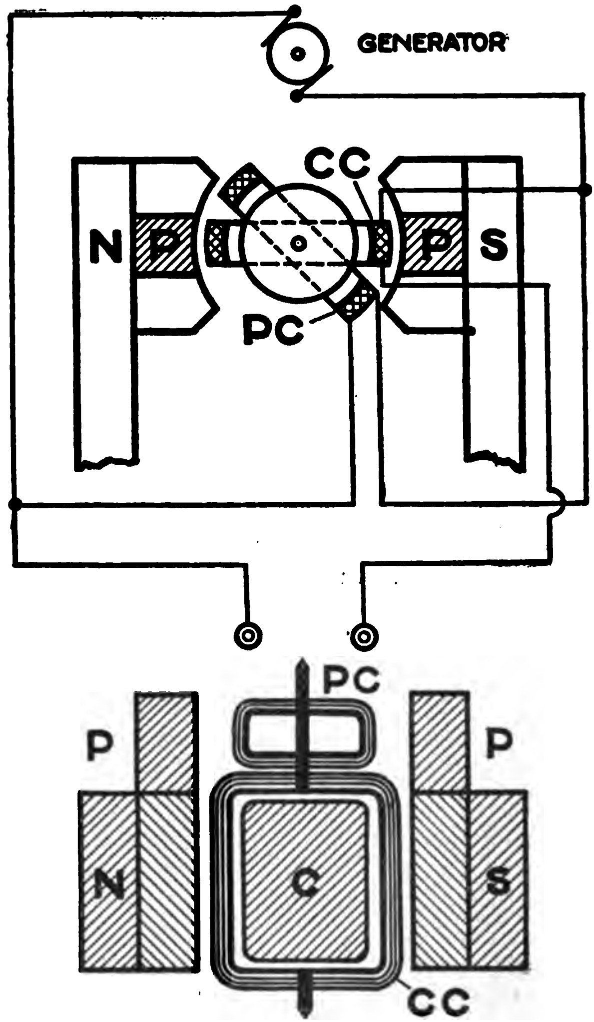


FIG. 53.—The " Metrohm."

upper, so that approximately the same percentage accuracy is possible throughout (see p. 9). The same magnetic system

furnishes the field for both the instrument and the generator, and since both the pressure and current coils move in a common field, the readings are independent of the strength of the magnet. Current is led into and out of the moving coils by means of three thin phosphor-bronze wire spirals, which exert a negligibly small torque on the moving system.

A simple instrument has recently been introduced known as the Everett-Edgcumbe "**Metrohm.**" The principle involved is much the same, but the arrangement of parts is quite different. As shown in Fig. 53, there are two moving coils, fixed one above the other to a common axis and each swinging in its own magnetic field. The lower (CC) is the

FIG. 54.—Scale of the "Metrohm."

current coil, and the upper (PC) the pressure coil. By suitably proportioning the upper pole pieces (PP), so as to graduate the strength of the magnetic field, a scale of any required openness can be obtained.

In order to give the maximum sensitiveness, the current coil turns in a narrow air-gap, while the pole pieces (PP) between which the pressure coil swings are so cut away as to give a strong field at the zero end of the scale and an excessively weak field at the infinity end. An actual scale is shown in Fig. 54.

The principle of the Nalder (Cox) ohmmeter, which is known as the "**Ohmer,**" is shown diagrammatically in Fig. 55. It is constructed on the electrostatic principle, and, in order to secure sufficient power, a number (thirteen in all) of vanes (V) are placed one above the other on the spindle, working in a corresponding number of fixed cells, A, B. In the actual instrument there are four sets of cells, those dia-

metrically opposite being connected together, but only two are shown in Fig. 55, for the sake of clearness. In use, the terminal E is connected to "earth," and the terminal L to the circuit to be tested. On turning the handle of the generator, which is contained in the ohmmeter case, the same difference of potential is established between A and V as between B and V. The pointer, therefore, comes to rest at ∞ so long as the resistance between E and L is infinite. If, however, a circuit

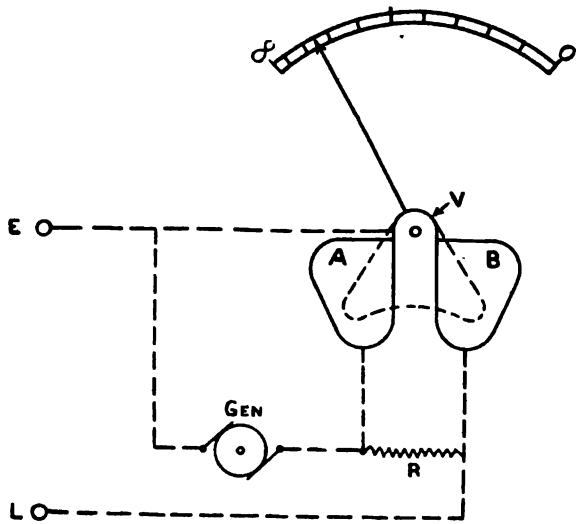


FIG. 55.—The "Ohmer."

is established between them, owing to a fault in the insulation under test, a current will flow through the resistance R; and, as a consequence, the potentials of A and B will no longer be the same (owing to the drop in volts along R). There will, therefore, be reduced attraction between V and B, so that the former will take up a new position, depending on the strength of the current flowing. It will be seen that this position is quite independent of the voltage of the generator, as any variation in this will affect the potential difference between V and A and that between V and B, equally.

It is now customary to test all installations, machines, etc.,

for insulation, at 500 volts, at least, and in many instances a 1,000-volt test is specified. For this purpose small hand-operated magneto-generators have been devised by means of which these voltages can be obtained. Owing to the difficulty experienced with the ordinary commutator, it is usual to connect the various sections of the winding to separate two-part commutators, which are then connected in series by means of carbon brushes. Not less than four segments are essential in such commutators.

Although the ohmmeters described are independent of the applied pressure, at the same time, if the insulation under test has appreciable capacity, any sudden change of pressure produces a throw on the pointer, owing to the capacity current flowing into or out of the capacity. For this reason a **steady pressure** is essential for cable testing. The two most usual methods of ensuring this are either to drive the generator by means of a small motor or to introduce a slipping clutch between the driving handle and the generator, arranged to slip at a definite speed, above which the generator is driven at an almost constant speed.[1]

Both the "Megger" and the "Metrohm" principles can be used for the measurement of comparatively **low resistances.** For an instrument intended to measure up to, say, 100 ohms, little or no modification in principle is required, but for resistances below this some changes are necessary, owing chiefly to the fact that the necessary testing current becomes too large to be passed through the current coil. As in the case of a moving coil ammeter, for larger currents than the moving coil can carry, use is made of a shunt. The resistance to be measured is, in fact, connected in parallel with one coil, and a known resistance with the other. In this way, the range of a moving coil ohmmeter can be increased to an almost unlimited extent. This is the principle adopted in the Evershed "**Ducter ohmmeter.**"

In order to simplify the operation, special hand contacts

[1] An ingenious method of testing an ohmmeter and generator by means of the supply voltage and a voltmeter is given by Stubbings (*Electrical Review*, Vol. 81, p. 315: 1917).

can be arranged, each provided with two spikes, the one for leading the current into the resistance to be measured and the other acting as a potential contact. The arrangement is shown, diagrammatically, in Fig. 56. CC represents the current coil, and PC the potential coil. The two spikes Sc, Sc, lead the current into the resistance under test, and the two others (S_R, S_R) connect the potential coil to the end points of this resistance. Each pair of spikes is mounted

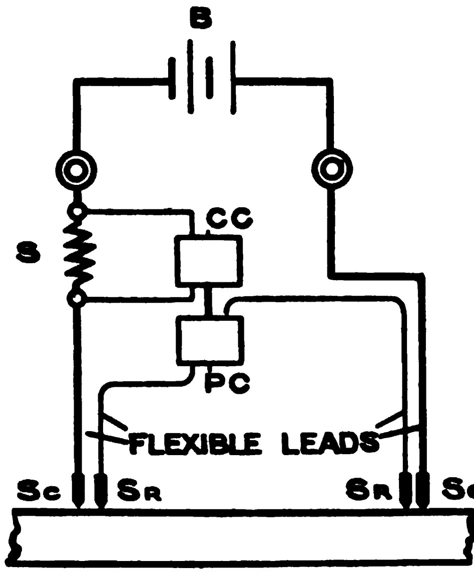


FIG. 56.—Ohmmeter for very Low Resistances.

in a handle, one of them being pressed down by a spring, so that the measurement of resistance, in this way, is extremely simple. The resistance shunting the current coil (shown at S) can be varied so as to give any required range. In order to avoid damaging the instrument, a very sensitive electro-magnetic cut-out is fitted, which in the event of a short circuit, disconnects it.

For those cases in which an open scale is required, and the range to be covered is small (as, for example, in connection with resistance pyrometers), Harris has applied the differen-

tial principle to his ohmmeter (see p. 104) in the following way. In Fig. 57 P_1 represents the pressure coil, and C the current coil, these two being connected up in the way already described. Wound by the side of C is a second pressure coil, P_2, the current in which opposes that in C. Suppose the range which is to be covered by the instrument is 50 to 200 ohms (as might well be the case with a resistance pyrometer), the numbers of turns in P_2 and C are so proportioned that with 50 ohms connected at *R* their ampere turns are equal and, as they oppose one another, the resultant torque is zero. Any increase in the resistance *R* will reduce the ampere turns of C, those of P_2 remaining unchanged, and as the effective torque depends upon their *difference*,

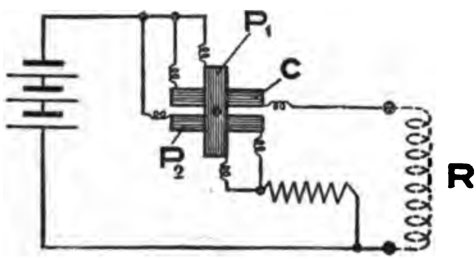


FIG. 57.—Harris Differential Ohmmeter.

the deflection is very much greater for a given increase in *R* than would be the case if the coil P_2 were omitted.

The Potentiometer.

As the name implies, the potentiometer is an instrument intended primarily for the accurate measurement of potential. Its useful range is usually from 1 micro-volt to 1 or 1·5 volt, and in conjunction with a set of standard shunts and resistances it may also be employed for any desired range of current and pressure. Similarly, it can be adapted to the accurate measurement of resistance by the volt drop method, in which the "drop voltmeter" is replaced by the potentiometer. Although available for all ranges of resistance, its most useful application is to measurements

of less than 1 ohm, to those, in fact, below the range of the Wheatstone bridge (see p. 98).

The potentiometer is essentially a continuous current instrument, though an apparatus on the same lines has been developed by Drysdale for alternating current (see p. 118).

The forms most commonly in use may be classified as—

(*a*) The simple potentiometer.
(*b*) The universal or double potentiometer.
(*c*) The low reading potentiometer.
(*d*) The deflectional potentiometer.

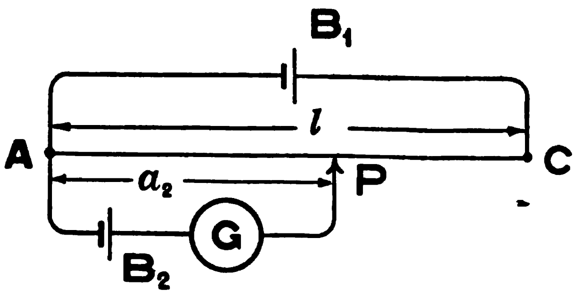


FIG. 58.—Simple Potentiometer.

(*a*) The principle of the **simple potentiometer** may be gathered from Fig. 58. B_1 is a source of steady current, such as an accumulator, and across its terminals a stretched wire, AC, is connected, the resistance of which is unimportant so long as it is uniform throughout its length. If, now, a cell, B_2, of lower E.M.F. than B_1, is connected through a galvanometer, across a section of the wire, as shown, it is clear that, by moving the contact P along the wire, a position may be found at which the fall of potential from A to P is equal to the E.M.F. of the cell B_2. This point will be indicated by the galvanometer pointer remaining at zero when contact is made. Then, if V_1 = pressure drop along the whole wire and V_2 = E.M.F. of B_2—

$$\frac{V_2}{V_1} = \frac{a_2}{l},$$

where l is the total length of the wire and a_2 is the distance from the point of balance P to the end common to both circuits. Hence—

$$V_2 = \frac{a_2}{l} \times V_1.$$

If, then, V_2 is a standard cell of known E.M.F., the voltage drop along the whole wire can be accurately calculated. In practical instruments it is customary to replace the simple wire by a series of resistances; and, instead of varying the proportion of a_2 to l by moving a contact point, the magnitude of the whole resistance is varied, and the part equivalent to a_2 is kept constant. Fig. 59 shows the connections of a simple

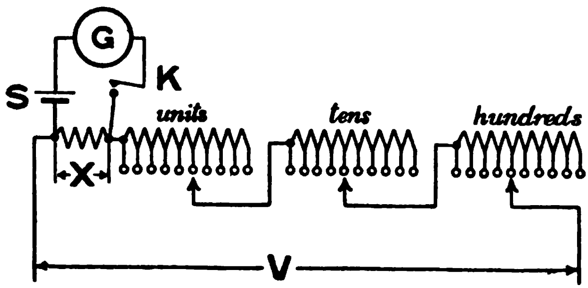


Fig. 59.—Modified Simple Potentiometer.

potentiometer constructed on these lines. The pressure to be measured is applied at V. S is the standard cell, G and K the galvanometer and key. The value of the resistance X is made equal in resistance units to the E.M.F. of the standard cell (S) in volts.

This instrument is only suitable for the measurement of pressures above, say, 2 volts, but is sensitive and accurate, besides being convenient to use. The resistance is usually so chosen that a current of the order of $\frac{1}{100}$ ampere is taken from the supply when a balance has been obtained.

(*b*) For the measurement of pressures less than $1\frac{1}{2}$ to 2 volts the **universal or double potentiometer** is required. Referring again to Fig. 58, it will be observed that if the

cell B_2 is replaced by another cell, B_3, and a balance obtained for this at, say, a_3, then—

$$\frac{V_3}{V_2} = \frac{a_3}{a_2}, \text{ or } V_3 = \frac{a_3}{a_2} \times V_2.$$

Hence, if B_2 is a standard cell of known E.M.F., that of B_3 can be at once calculated.

In the practical forms of this potentiometer the slide-wire shown in Fig. 58 is usually extended by the addition of a set of resistance coils in series, while the actual slide-wire takes up but a small fraction of a volt. Each resistance

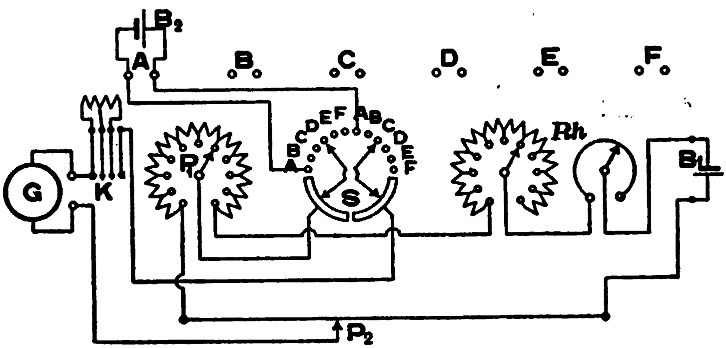


FIG. 60.—Crompton Potentiometer.

step is equal to 100 divisions on the slide-wire scale, and the overall voltage is also adjusted in such a manner that each step (or 100 divisions on the slide-wire) represents $\frac{1}{10}$ or $\frac{1}{100}$ volt and the proportionality of $\frac{a_3}{a_2}$ can be read direct.

A good example of this instrument is the **Crompton** potentiometer, of which a diagram of connections is given in Fig. 60. In this instrument the slide-wire is extended by connecting in series with it fourteen resistance steps, the value of each step being adjusted to precisely $\frac{1}{10}$ volt, this being also the voltage drop along 100 divisions of the slide-wire. Two movable contacts are used, one of which, P_1, passes over studs connected to the ends of the resistance steps, while the other, P_2, makes contact with the slide-wire.

By this means it is possible to vary the distance between the contact points by an amount equal to any number of resistance steps plus any fraction of the stretched wire. Thus the arrangement is equivalent to having a wire fifteen times as long as that actually employed. Moreover, the accuracy is much less dependent on the degree of uniformity of the wire with regard to its resistance per unit length. The wire is actually about 2 ft. 6 ins. long, and is divided into 105 parts, so that the accuracy of reading and adjustment is the same as if a single wire 37 ft. 6 ins. long was employed. The advantage of having the extra five divisions on the wire is that it enables a reading just beyond the upper limit of the wire to be taken without the necessity for running the slide-wire contact along the whole travel.

The remainder of the equipment consists of a rheostat, Rh, with coarse and fine adjustments for regulating the current, a double pole selector switch, S, and a press key, K, for closing the galvanometer circuit. This key is provided with four blades, arranged one above the other, with a resistance coil connected between the two lower blades and another between the two centre blades. On pressing the key the galvanometer circuit is closed, first, through a high resistance, then through one of lower value, and finally all resistance is cut out. In this way, the operator is warned if there is considerable want of balance, as soon as the first pair of contacts is closed, and the risk of damaging the galvanometer is minimised. A single accumulator cell, B_1, is used to supply current to the wire, and a standard cell, B_2 (see p. 122), is connected to the first pair of terminals, A. The selector switch S enables the external circuit connected to any pair of terminals A, B, C, D, E, or F, to be connected in series with the galvanometer, so that it is easy to make measurements on two or more circuits in rapid succession.

As the instrument is intended to read $\frac{1}{10}$ volt per resistance step, the first operation consists in balancing the E.M.F. of the standard cell against a corresponding setting (say 1·0184) on the instrument. The current through the wire is adjusted for this purpose by means of the rheostat Rh. The instru-

ment is then ready to measure any pressure (up to $1\frac{1}{2}$ volt) which may be applied to one of the pairs of terminals. For the measurement of pressures above this value a **ratio resistance,** or "**volt-box,**" is employed (see Fig. 61). This consists of a high resistance, AB, with accurate tappings, T_1, T_2, T_3, etc., so arranged that V is a definite and known multiple of V. Since there is no current passing in the galvanometer circuit at the instant the measurement is made, the voltage V may be accurately determined by multiplying the reading of the potentiometer V by the ratio of the whole resistance to the fraction across which the potentiometer is connected.

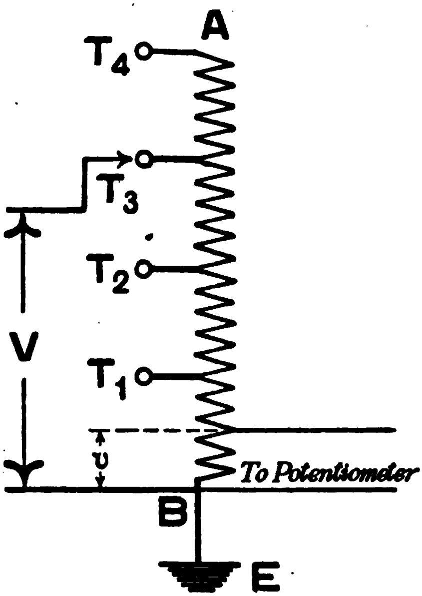


FIG. 61.—Potentiometer Volt-box.

This method is obviously not so direct as that of the simple potentiometer shown in Fig. 59, but it has the advantage of being applicable to a variety of other measurements.

(c) The universal potentiometer principle also lends itself well to the measurement of **very low pressures** on account of its sensitiveness and accuracy. It is desirable, in this case, to use a low voltage over the whole instrument and, to this end, a resistance is connected in series with the slide-wire, after calibrating against the standard cell.

It should be remembered, in using a potentiometer in this way, that thermo-E.M.F.'s become of special importance, and the utmost care must be taken to minimise them at all

contacts and, if unavoidable, to observe their magnitude and correct the results accordingly.[1]

(*d*) **Deflectional Potentiometers.**—A disadvantage of the simple potentiometer for many purposes lies in the time taken to obtain a balance, so that it is often impossible to employ the ordinary form on circuits with even slightly varying pressures. For such cases a potentiometer has been designed in which it is not necessary to obtain an exact adjustment, a slight want of balance being indicated by a galvanometer calibrated in millivolts.

The principle is shown in Fig. 62, in which the ordinary potentiometer circuit is shown by the letters A, B, C, D, Rh, B_1,

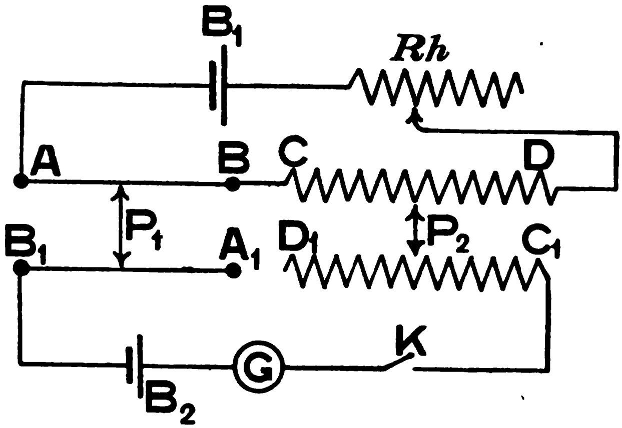


FIG. 62.—Deflectional Potentiometer.

the slide-wire and its extension resistances being marked A, B, C, D. B_2 is the potential to be measured, and is connected in the galvanometer circuit, which also includes a slide-wire, B_1 A_1, and set of resistances, D_1 C_1, which are facsimiles of the slide-wire and extension resistances in the main potentiometer circuit. By a simple mechanical arrangement the travelling contacts P_1 and P_2 travel over both sets of slide-wires and resistances in such a way that the total resistance included in the galvanometer circuit remains constant. It will be seen that any increase in CP_2 is balanced

[1] See also pp. 49 and 121.

by a corresponding decrease in $C_1 P_2$, and *vice versâ*. Similarly $B_1 P_1$ counteracts any change in BP_1.[1] In this way, the current flowing (as indicated by the galvanometer deflection) is a measure of the difference between the E.M.F. of B_2 and the fall of potential along the resistance between P_1 and P_2.

As this is not a null method of measurement, it is only strictly applicable to the measurement of potentials, which are not affected in value by a slight flow of current through the apparatus. For example, if B_2 is an electrolytic cell, its internal resistance must be negligible compared with that in the remainder of the galvanometer circuit, or the value found will not be a true measure of the E.M.F.

Deflectional potentiometers are considerably more sensitive than any form of direct reading instrument, and are particularly useful for accurate pyrometer work.

(*e*) In the Drysdale **alternating current potentiometer**[2] provision is made for measuring the phase as well as the magnitude of a P.D. The current through the slide-wire is supplied from a graduated "phase-shifting transformer," which enables it to be turned through any desired angle with regard to the pressure. A sensitive dynamometer ammeter is connected in series to indicate when the alternating current through the wire has the prescribed value. A vibration galvanometer is employed to indicate balance, instead of an ordinary galvanometer, as in the potentiometers already described. The essential connections are outlined in Fig. 63, but in the actual instrument are somewhat more elaborate.

In use, the potentiometer is first standardised on continuous current in the usual way by throwing both the switches X and Y into the left-hand position, when it will be seen that the ordinary universal potentiometer connections are obtained and the current through the wire is adjusted to give a definite value (say 0·1 volt) per step. The switch

[1] *Bulletin Bureau of Standards*, Vol 8, No. 2, "Outline of Design of Deflectional Potentiometers, with Notes on the Design of Moving Coil Galvanometers," by H. B. Brooks.

[2] *Electrician*, Vol. 75, p. 157 (1915). For a description of some A.C. potentiometers which do not involve a phase-shifting transformer, see Déguisne, *Archiv. f. Elek.*, Vol. 5, p. 303 (1917).

arms are then put on the right-hand contacts and the current adjusted until the same R.M.S. value is shown by the dynamometer D. Let it be assumed that to one of the circuits (I., II., III., etc.) of the distributing switch DS there is applied an unknown alternating pressure of exactly the same frequency as the potentiometer supply and of suitable magnitude. By adjusting the position of the secondary of the phase-shifting transformer PST it is possible to find a position at which the deflection of the vibration galvano-

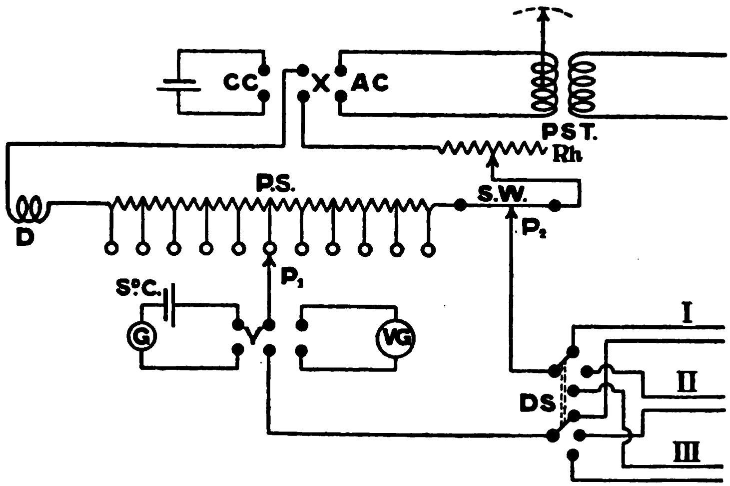


FIG. 63.—Drysdale Alternating Current Potentiometer.

meter VG is a maximum, thus indicating that the unknown E.M.F. is approximately in phase with the P.D. at the terminals of the potentiometer. Now, by varying the distance between the contact points P_1 and P_2 for minimum deflection on the vibration galvanometer a fairly accurate balance of the magnitude of the voltages can be arrived at. The adjustment may then be repeated both with regard to phase and magnitude, and in this way it is possible to get a precise balance with both. The magnitude of the voltage is then read on the potentiometer scale and of the phase angle on that attached to the phase-shifting transformer.

By the use of shunts and ratio resistances the method

may be applied to the measurement of current and pressure in the same way as in the continuous current universal potentiometer.

All resistances employed in this potentiometer must be perfectly non-reactive, so that alternating and continuous currents produce precisely the same drop for the same R.M.S. values, and also that no phase displacement is introduced by the apparatus itself.

This potentiometer is said to be capable of an accuracy of $\pm \frac{1}{10}$ per cent. at all frequencies up to 1,000, or more, periods per second. Owing to the use of a vibration galvanometer, it follows that, unless the wave forms are similar, the instrument does not measure R.M.S. values, but the error actually introduced on this account is usually very small, say 0·1 per cent. for a 5 per cent. harmonic.[1]

Considerable care has been devoted to the design of the **phase-shifting transformer.** It consists of a stator and rotor, very similar to those of an induction motor, carrying two-phase or three-phase windings, according to the source of supply. The stator produces a rotating field, and thus induces an E.M.F. in the rotor which remains constant in magnitude for all positions of the latter. The change of phase between primary and secondary P.D. is almost proportional to the angle through which the rotor, which carries a pointer moving over a scale of angles and cosines, is turned. If the primary current has a sine wave form, the secondary will also approximate closely to a sine wave, and an accuracy of 0·1° or 0·2° is possible with care. On single phase systems the two-phase shifter is used, one of the windings being connected in series with a condenser of about 20 m.f. capacity, which is shunted by a resistance of about 1,000 ohms. These phase-shifting transformers can also be used for energising the pressure circuits of wattmeters, watt-hour meters, or power factor meters during test, and although they have a considerable drop between no load and full load, the pressure is almost independent of the angle turned through, and they can be used at all ordinary frequencies.

[1] *Electrician*, Vol. 77, p. 857 (1916).

The **vibration galvanometer** employed with this potentiometer is a modification of the Thompson type, with a very light movable system and a strong adjustable controlling field, so that the natural time of vibration may be tuned to agreement with the frequencies ordinarily met with. Instruments of this type are liable to be affected by external mechanical vibration and by stray alternating magnetic fields of the same frequency as that to which the system is tuned. Mechanical vibration may usually be eliminated by mounting the instrument on a heavy base with an intervening buffer of soft cloth or rubber. The best way of dealing with stray fields is to place the instrument at a considerable distance from the working circuit, and, as far as possible, to twist all leads together in pairs.

The most serious sources of error in potentiometers are **leakage currents and thermo-E.M.F.'s.** The former require particular attention when measuring pressures above 100 volts, while the latter are mainly noticeable in connection with the measurement of very low P.D.'s, such as obtain in current measurement by the voltage drop method.

Leakage errors may usually be eliminated if the galvanometer is very carefully insulated, as, for example, by standing it upon a block of ebonite. Further the surface of all insulation must be kept free from dust, and if of ebonite, should not be exposed continually to the action of light, and particularly of strong sunlight. If the circuit on which a measurement is being made is known to be earthed, the potentiometer connections should be arranged so that the galvanometer is at or near earth's potential. When circumstances permit, it is a good plan actually to earth-connect the ratio box and the common terminal B (see Fig. 61).

The elimination of thermo-E.M.F.'s when using the instrument for precise current measurements is ensured, mainly, by the use of manganin shunts (see p. 46), but there are many other applications which present some difficulty in this respect. To detect such thermo-E.M.F.'s the current can be switched off the circuit under test and the potentiometer contacts set at zero. Should any deflection be

observed on the galvanometer, this may be balanced, in the usual way, by moving the sliding contacts, the value of the reading so obtained being added to or subtracted from the reading obtained with the test current. As the thermo-E.M.F. reading may be negative, it is well to provide a reversing switch in circuit with the accumulator which supplies the slide-wire current.

With reference to errors caused by thermo-E.M.F.'s, it may be pointed out that these are frequently generated within the potentiometer itself unless it has been carefully designed to avoid these effects. Rapid movement of any of the sliding contacts is liable to cause sufficient heating to generate quite an appreciable thermo-E.M.F. if the contacts are not of suitable metal, and even some of the best instruments are not above criticism in this respect.

Standard Cells.

The forms commonly in use are—

(1) The **Clark** cell, as adopted for the definition of the legal volt by the Board of Trade. The constituents are (mercury) mercurous sulphate, zinc sulphate (zinc).

The E.M.F. of this cell is 1·4328 international volt at a temperature of 15° C., and falls ·083 per cent. per degree rise of temperature.

(2) The **Muirhead** and **Carhart** modifications of the Clark cell. These have the same E.M.F. as the Clark cell, but have a reduced temperature coefficient. The former cell has a lower internal resistance, and recovers more rapidly from short-circuiting than does the Board of Trade pattern.

(3) The **cadmium** or **Weston** cell. This is similar to the Clark except that cadmium is substituted for zinc. It has an exceptionally low temperature coefficient (only 0·00005 volt decrease per degree Centigrade rise), and has the property of recovering rapidly after short-circuiting. It is of particular interest in that it is the form of cell which was used for a comparison of the standards of voltage in use in the National Physical Laboratory, the American Bureau of Standards, the Laboratoire Central of France, and the

German Reichsanstalt. Its E.M.F. is usually given at 20° C., and is 1·0184 international volt at this temperature. This is the form of cell now most generally recommended for potentiometer use.

(4) The **Hibbert** cell, which is similar to the Clark, but for the substitution of chlorides for the sulphates of zinc and mercury. It is particularly interesting in that its E.M.F. is 1 volt at 15° C., the temperature coefficient being only 0·01 per cent. fall per degree Centigrade rise.

Galvanometers.[1]

All bridge and potentiometer methods depend on the employment of a sensitive galvanometer. There are two main types :—

(*a*) The suspended magnetic needle or Thomson type.

(*b*) The suspended coil or Deprez-D'Arsonval type.

There is a great variety of other, subsidiary, types, such as vibration galvanometers (see p. 121), thermo-galvanometers (see p. 164), dynamometer galvanometers, string galvanometers, etc. These latter are, however, of restricted interest.

In the **suspended needle type**, a magnetic needle is hung by a torsionless quartz or silk fibre within a coil whose axis is horizontal. The needle is held in a position at right angles to the axis of the coils by a controlling magnetic field, this being either the earth's field or that due to a fixed magnet attached to the instrument. Current through the coil tends to force the needle parallel to the axis of the coil.

For insulation work advantage is taken of the extreme sensitiveness of this class of instrument. It is possible to detect currents as small as one millionth of a micro-ampere $\left(\frac{1}{10^{12}}\text{ ampere}\right)$.

The **suspended coil or D'Arsonval** type is illustrated in Fig. 64, from which it may be seen to consist essentially of a permanent magnet, M, in the field of which is suspended or pivoted the moving coil M C, in such a way as to be capable

[1] For vibration galvanometers, see p. 121.

of rotating about its vertical axis in the comparatively narrow arc gap between the pole pieces and the core C. To the coil is attached either a mirror or a pointer. Control is usually provided by a suspension consisting of a fine strip of phosphor-bronze, which also serves to lead the current into the coil. It is led out again by means of a similar strip or of a fine spiral below the coil. In other cases two strips are used so as to produce a bifilar suspension, or, again, when pivots are employed, the control takes the form of a light helical spring.[1] A very successful pivoted D'Arsonval type of galvanometer is that of **Paul,** in which the core is spherical, and only one pivot is employed, this being at the centre of the coil. By this means the need for accurate levelling is avoided, and the friction is much less than that for two pivots. These "Unipivot" instruments are very convenient for portable use where the highest degree of sensitiveness is not so important as comparative robustness.

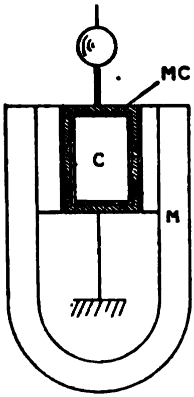


FIG. 64.—D'Arsonval Galvanometer.

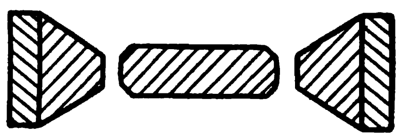


FIG. 65.—Pole Pieces of Galvanometer sensitive at Zero.

For Wheatstone bridge work, as in fact for all null or zero methods, it is important that the sensitiveness of the galvanometer should be a maximum at the point of rest, while readings away from zero are of little importance. For this purpose the poles of the magnet are usually shaped as in Fig. 65, whereby a very intense field is obtained over a narrow range. When the instrument is required to give readings of current over a wide range, on the other hand, the

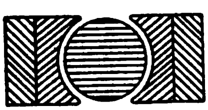


FIG. 66.—Pole Pieces of Galvanometer for Proportional Scale.

[1] See also p. 29.

poles and core are, as a rule, arranged as in Fig. 66, so that the field is as uniform as possible and proportionality between current and deflection is obtained.

The methods commonly employed for **magnifying the deflections** are—

(1) By a pointer attached to the movable system passing over a divided scale.
(2) By a beam of light reflected on to a scale from a mirror attached to the movable system.
(3) By looking through a telescope at the image of a fixed scale reflected in a mirror attached to the movable system.

The telescope method (3) is objectionable on account of the eye strain involved, and, although popular in the United States and in Germany, it has never found much favour in Great Britain. Method (2) is extremely useful, and is the standard practice where great sensitiveness of reading is desired. The angle swept out by the beam of light coming from the mirror is double that through which the movement turns, and as the scale may be at a great distance from the instrument, the magnification of the motion can be increased to almost any desired extent. Modern practice favours the use of large mirrors accurately ground and brilliantly illuminated, so that the indications can be observed without resorting to the use of a darkened room. A mirror 1 to 1½ cm. in diameter gives excellent results if illuminated by a 50-watt nitrogen-filled lamp, while by using an arc for illumination perfectly clear indications may be obtained on a scale 50 ft. away from the instrument.

Pivoted galvanometers are not, generally, suitable for use except with a simple pointer and scale, as the effect of pivot friction becomes very noticeable with the more sensitive optical methods of magnification.

The **sensitiveness of a galvanometer** is measured fundamentally in terms of the watts required to produce a certain scale deflection, and this may again be referred to in terms of the watts for unit angle of deflection or for the length of

scale corresponding to unit angle. Thus, in choosing a galvanometer, it is necessary to make a distinction between the sensitiveness of the instrument itself and that due to the multiplication produced by the pointer or mirror.

In general, it may be said that for maximum working sensitiveness the **resistance of the galvanometer** winding should be of the same order as that of the circuit on which measurements are being made. The following table may serve as a guide in this respect :—

Nature of Test.	Suitable Galvanometer Resistance.
Low temperature thermo-couple pyrometry . . . . . ; Low reading potentiometers .	20 to 100 ohms.
Universal potentiometer . . . ; Kelvin bridge	100 to 1,000 "
Wheatstone bridge up to 10,000 ohms	100 to 2,000 "
" " up to 100,000 "	500 to 4,000 "
Resistance measurements from 100,000 ohms to 1,000 megohms and insulation testing generally . . .	5,000 to 20,000 ohms (only available in Thomson type).

Galvanometers of the suspended magnet type are not usually damped, but slight air **damping** is sometimes obtained by attaching a mica vane to the swinging system. When a moving coil galvanometer is to be damped the coil is wound on a copper or aluminium frame or former, as in the case of moving coil ammeters and voltmeters (see p. 144).

Considerable damping is also obtained, in this type, when used on closed circuit, owing to the currents generated within the coil itself by its motion through the field, so that it is usually unnecessary to employ a metal former.

Standard Methods of Current Measurement.

The legal definition of current strength is in terms of its electro-chemical action,[1] and for fundamental determinations with continuous current the **copper voltameter** may be used with fair accuracy. The usual method of continuous current standardisation, however, is by means of the **potentiometer,** together with a standard low resistance, or "shunt" (see p. 45). This method is extremely accurate and fairly rapid.

For alternating current the choice lies between various types of standard **dynamometer** and the **electrostatic** voltmeter method.

The **Kelvin balance** is a form of dynamometer ammeter adapted to the measurement of current up to 10,000 amperes.

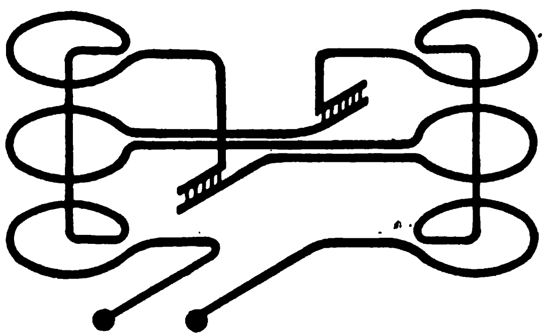


FIG. 67.—Kelvin Balance.

The instrument consists of two coils fixed one at each end of a swinging beam, which allows them to oscillate between two other pairs of coils, as shown in Fig. 67. The current to be measured is passed through the fixed coils in series, being led into the pair of moving coils by means of a suspension formed of a great number of very thin copper wires, in parallel. As a result of the electro-magnetic interaction between the coils, the left-hand end of the beam is depressed and the right-hand end elevated. The equilibrium of the

[1] The ampere is that steady current which deposits silver from an aqueous solution of its nitrate at the rate of 0·001118 gramme per second.

beam is restored by moving a rider or sliding weight along it, a scale being provided to indicate the effective couple exerted by the weight. The instrument is thus controlled by gravity.

These balances are made in various capacities, and each has four sliding weights with corresponding counterweights, so that an extended range is obtained. Their natural scale follows a square law, since the current acts upon itself, but the scale on the beam is uniformly divided, and the current has to be deduced from the expression—

$$\text{current} = \sqrt{\text{reading}} \times \text{a constant.}$$

The constant is usually determined by a calibration on continuous current against a potentiometer, after which it may be employed for the measurement of the R.M.S. value of an alternating current of any wave form or frequency usually met with on lighting or power circuits.[1]

The arrangement of coils adopted in the Kelvin balance is astatic as regards stray fields of uniform intensity, but a certain amount of care must be taken in arranging any heavy current leads in the vicinity of the instrument, since these may produce a strong field in the neighbourhood of one moving coil and little or none in that of the other.

These balances are also made up as voltmeters and wattmeters, but the latter are not suitable for accurate alternating current measurements without the application of tedious corrections for the self-induction of the windings.

The **Siemens dynamometer** has also been employed to a large extent as a standard for alternating current measurements, but is now little used on account of its extreme susceptibility to errors due to stray fields and its general crudeness of construction, necessitating extremely careful manipulation to obtain accurate results. The fixed and swinging coils are placed one within the other, and at right angles, about a common vertical axis. Current is led into and away from the moving coil by mercury wells, and the torque due

[1] The heavy current types are not very accurate for alternating currents, particularly at high frequencies, on account of the tendency of the current to concentrate in the outer parts of the conductor. The difficulty may be largely overcome by the use of stranded conductors.

to the current is balanced against that of a helical spring, which can be twisted up until a pointer attached to the moving coil returns to zero. The angle through which the fixed end of the spring has been turned is read off an evenly divided circular scale at the top of the instrument, and the current value deduced therefrom by means of a similar expression to that employed for the Kelvin balance.

Deflectional dynamometer instruments may also be used with accuracy for alternating current after calibration on continuous current, provided that there is only a single series path through the instrument (see also p. 177).

The **electrostatic voltmeter method** can only be regarded as suitable for a final standard of reference when applied to small currents, say under 1 ampere. In its simplest form it consists in measuring the voltage drop across a non-inductive shunt, the resistance of the shunt having first been measured and the voltmeter calibrated by a continuous current method. It is evident that a P.D. of say 100 volts (which is probably the minimum allowable for the satisfactory operation of a standard electrostatic voltmeter) is prohibitive as a shunt drop for all but the smallest currents.

This difficulty has been overcome, however, by **Campbell** by the use of a small transformer which converts the low P.D. at the shunt terminals into a high secondary pressure, suitable for the operation of the voltmeter. The transformer used must possess perfect constancy of ratio over a wide range of frequency and take a negligible magnetising current. If these conditions are fulfilled, the method is applicable to alternating currents of all magnitudes by the provision of suitable shunts. This method is in use at the National Physical Laboratory for current standardisation.[1]

Standard Methods of Pressure Measurement.

For continuous current work the **potentiometer** method) described on p. 111, is almost invariably used as a final

[1] For full details see a paper by Paterson, Rayner and McKinnes, *Journal Inst. E.E.*, Vol. 51, p. 294 (1913).

standard of reference, on account of its accuracy and convenience.

The ordinary **electrostatic voltmeter** affords a most useful means of standardising on alternating current, if previously calibrated on continuous current by the potentiometer. This is the method adopted by the National Physical Laboratory for alternating current work.[1] A **dynamometer** instrument may also be used for this purpose if sufficient idle resistance is used in series to make the effect of the self-induction of the windings negligible. This is, however, apt to necessitate the employment of a somewhat large operating current, which is not always convenient, and some workers prefer to construct a curve of corrections for different frequencies, calculated from a knowledge of the self-induction and capacity of the instrument.

Calibrated Spark Gap for Pressure Testing.

When direct measurements of E.H.T. pressures have to be made and an electrostatic voltmeter is not available, the spark gap, if carefully designed and used, forms a useful method and is recommended by the American Institute of Electrical Engineers[2] for the purpose.

Such gaps usually take one of two forms, viz., the **needle gap** or the **sphere gap**. The former consists of a pair of No. 00 sewing needles, and the latter of a pair of large spheres, usually about 5 ins. in diameter, but ranging up to as much as 18 ins. for pressures of 400,000 volts. The sphere gap is preferable above 30,000 volts, but below this pressure the wider gap jumped by a given pressure with the needle gap makes this latter the more satisfactory.

The **spark-over pressure** at 25° C. and 760 mms. atmospheric pressure, assuming a sinusoidal wave form, is given in the table on p. 131.

The figures refer to tests in which both poles are insulated from earth, but for the ranges given the difference when one pole is earthed is negligible. For higher pressures

[1] See footnote to p. 129.
[2] Standardisation Rules of Am. Inst. Elec. Eng., 1915, para. 530 *et seq.*

the gap bridged is considerably increased by earthing one pole. For small variations of **atmospheric pressure** the spark-over voltage for a given gap may be assumed to vary in direct proportion with the pressure.

Pressure in Thousands of Volts.	Gap Length in Millimetres.		
	Needles.	125-mm. Spheres.	500-mm. Spheres.
10	11·9	—	—
15	18·4	—	—
20	25·4	—	—
25	33·0	—	—
30	41·0	14·1	—
40	62·0	19·1	—
50	90·0	24·4	—
60	—	30·0	—
80	—	42·0	41
100	—	55·0	51
200	—	—	106
300	—	—	171
400	—	—	257

The effect of frequency on the spark-over pressure is very small in the case of the sphere gap, being negligible up to 1,000 periods and only 10 per cent. or 15 per cent. at 40,000 periods.[1]

There should be a clear space round the gap equal to, at least, twice the length of gap in the case of the needle gap, and to twice the sphere diameter in the case of the sphere gap. Considerable care is required in the measurement of the diameter and curvature of the spheres. The former should not differ by more than 0·1 per cent. and the latter by more than 1·0 per cent. from the true value. If these various precautions are taken an accuracy of 2 per cent. in the pressure measurement may be looked for.

In order to **protect the apparatus under test from over-pressures** due to high frequency oscillations set up by the spark, a non-inductive resistance of about 1 ohm per

[1] F. W. Peek, jun., *Proc. Am. Inst. Elec. Eng.*, Vol. 33, p. 889 (1915).

volt of test pressure should be inserted in series with the insulated pole of the gap, or half on each side if both poles are insulated. Such a resistance not only damps out oscillations, but prevents the flow of a heavy current when the gap sparks over. A water resistance is the best for the purpose, carbon being liable to break down under high pressures.

Moving Iron Ammeters and Voltmeters.

These instruments, which are often loosely spoken of as "electro-magnetic," "soft iron," or "gravity," may be divided into two main groups :—

(1) Those having a single piece of iron, which is drawn into a coil under the influence of the current to be measured.

(2) Those in which the moving iron is attracted or repelled by one or more fixed irons.

Before describing particular instruments it may be well, briefly, to consider their working in a general way, more particularly as it is a subject which has not received the attention it deserves. Taking the simplest case, that of two pieces of soft iron inside a solenoid, one of them fixed and the other attached by an arm to the spindle carrying the pointer (see Fig. 72), it is clear that the two will repel one another, and that with a force proportional to the product of their respective magnetic pole strengths. If the permeability of the iron can be regarded as constant throughout the range of the instrument, the field due to each will be proportional to the current flowing, so that the torque at every point is proportional to the square of that current.

This is a most important condition, since on the completeness with which it is fulfilled depends the suitability of the instrument for use with **alternating current,** for the following reasons. Since the effective value[1] of an alternat-

[1] An alternating current, having an "effective" (or R.M.S.) value of A amperes, has the same heating effect as a continuous current of A amperes.

ing current is represented by the square root of the mean (or average) square (R.M.S.) of the instantaneous values, it follows that an instrument, to give correct indications with alternating current, must have a torque which is proportional to the square of the current. This condition is fulfilled only so long as the permeability of the iron can be regarded as constant. Fig. 68 shows approximately the relation between permeability (μ) and induction (B) in a sample of

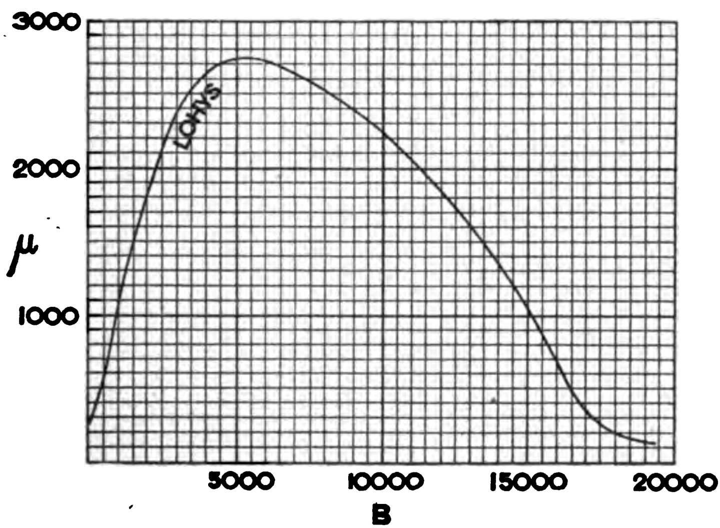


FIG. 68.—Permeability Curve of Lohys Iron.

good soft iron (Lohys iron). It will be seen that up to 4,500 lines per square centimetre the permeability increases rapidly. It then remains fairly constant up to 6,000, after which it falls off till a density of about 18,000 or 20,000 lines is reached, and then it becomes more and more nearly constant, or, in other words, the iron becomes saturated.

Wild has carried out[1] some experiments on the permeability of soft iron at extremely low induction densities, namely, below 120 lines per square centimetre. Fig. 69 gives curves for two brands of iron, Lohys (a good example of com-

[1] L. W. Wild, *Journal Inst. E.E.*, Vol. 52, p. 96 (1914).

mercial transformer iron) and Stalloy, which, besides showing less hysteresis, has a higher permeability than Lohys. An interesting feature brought out by these experiments is that the permeability at low densities is somewhat less with alternating current than with continuous current. This is shown for Stalloy by the dotted curve.

Yensen[1] found that the permeability could be nearly doubled at low inductions if the iron was purified by melting *in vacuo*, so as to prevent both the absorption of carbon and oxidation by the air. The hysteresis constant fell in about

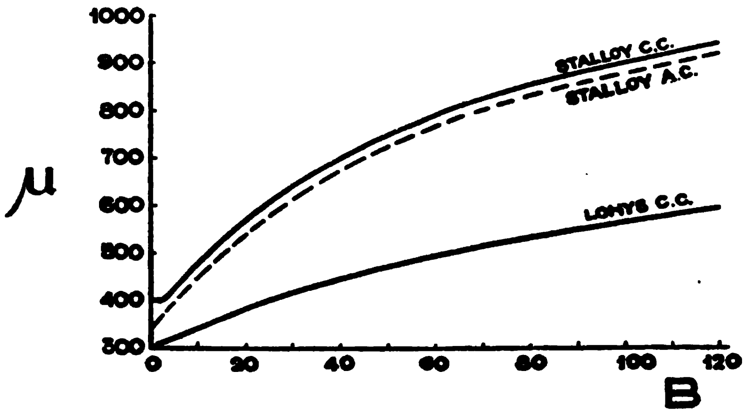


Fig. 69.—Permeability Curves of Lohys and Stalloy Iron.

the same proportion. This has been shown[2] to apply to pure (electrolytically prepared) iron and also to commercial soft iron.

If the iron in an instrument is saturated, the torque will be proportional to the current rather than to the square of the current, so that the deflection will depend upon the average value instead of the R.M.S. value. As a result, the indications will be affected by changes of wave form, since the ratio of R.M.S. value to mean value varies with the wave form. Such an instrument can be so calibrated as to

[1] T. D. Yensen, paper before American Institute of Electrical Engineers, *Electrician*, Vol. 75, p. 119 (1915).
[2] *Electrician*, Vol. 77, p. 533 (1916) and *E.T.Z.*, Vol. 36, p. 675 (1915).

read correctly on a circuit of any given wave form, but will be inaccurate on any other.

This effect is well shown in Fig. 70, which relates to an obsolete form of voltmeter, consisting of a long coil into which is sucked a thin iron wire, highly saturated. The instrument was calibrated with a voltage having a sine wave (curve C). Curve B shows the effect of an exceptionally pointed wave, and curve A of a very flat-topped wave. The difference in reading amounts in this case to some 10 per cent.

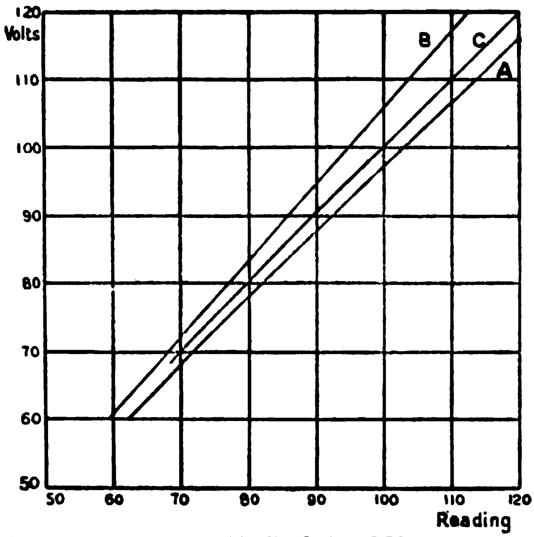


Fig. 70.—Effect of Wave Form of badly designed Moving Iron Instrument.

This may be contrasted with the results obtained by Burrowes[1] with an ammeter of modern construction, namely the "Universal" pattern (p. 141). Tests were made throughout the range with two wave forms of which the maximum ordinates differed by more than 50 per cent. for the same R.M.S. values. The effect on the readings was found to be *nil* within the limits of experimental error (about 0·3 per cent.).

The saturation effect also shows itself in a somewhat

[1] *Electrician*, Oct. 2nd, 1914, p. 995.

larger deflection being given with continuous current than with alternating current of the same R.M.S. value. In the latter case a higher induction is necessarily reached and, as a result of saturation, the flux density increases less than in proportion to the current (see also p. 84).

It is often assumed that if an instrument is unaffected by **changes of frequency**, it will have no wave form error. This is true of errors due to self-induction, but not of those due to magnetic saturation (see also p. 84). For example, a moving iron voltmeter having negligible self-induction, but a saturated iron core, will have no frequency error, although being much affected by wave form. On the other hand, one with considerable self-induction and an unsaturated core will show a large frequency error, but may be almost independent of wave form.

Eddy currents, whether in the windings or other masses of metal near the moving iron, may cause appreciable errors with increasing frequency, both by reducing the field strength and by altering its direction. For a given deflection, if I_0 is the current required at zero frequency and I_f at a frequency f, then—

$$I_f = \frac{I_0}{\sqrt{1 + kf^2}},$$

where k is a constant.

Another source of error in moving iron instruments is **hysteresis.** With **continuous current,** owing to the fact that the magnetism in the iron lags behind the current producing it, the reading obtained with a given current is always lower with a rising than with a falling current. To minimise this error two courses are open: (1) the induction in the iron can be made so low that the hysteresis is small, or (2) it can be made so high that the iron is practically saturated, and no hysteresis is possible. While either method can be followed in the case of continuous current instruments, the latter is inadmissible, as has already been shown, for use with alternating current. On the other hand, the weight of the moving parts is necessarily greater

in the former case. To reduce hysteresis to a minimum both the fixed and moving irons should be as short as possible in the direction of the magnetic flux, so that the self-demagnetisation (see p. 59) may be a maximum. The length of path of the magnetic lines in the iron should, moreover, form only a small portion of their total length, the remainder being in air.

The disturbing effects of hysteresis are not confined to continuous current instruments. With **alternating current,** owing to the fact that the magnetic flux in the iron always reverses after that due to the winding, it follows that

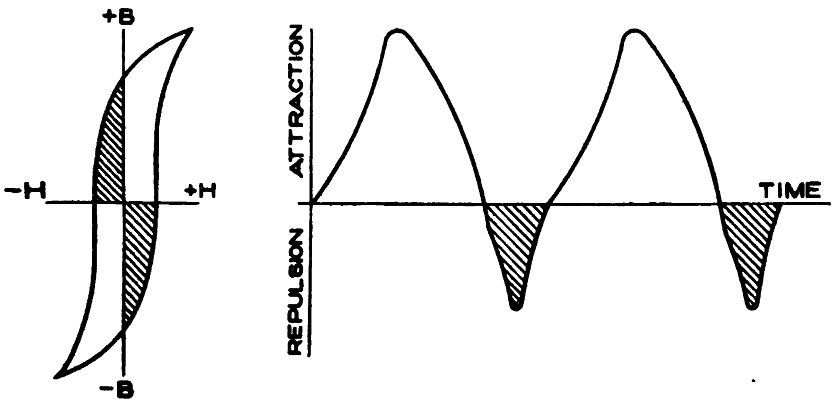


FIG. 71.—Effect of Hysteresis on a Moving Iron Instrument.

during each half-period there is repulsion as well as attraction, so that the instrument reads low. This is shown in Fig. 71, where the shaded areas represent this repulsion. The left-hand figure gives the B/H curve of the iron, H being the magnetising force due to the winding (directly proportional to the current to be measured) and B the flux density induced by it in the iron. The pull at any instant is dependent upon the product of B into H. Consequently, at those points on the B/H curve where B and H are of like sign the iron is attracted, whereas where the signs are opposite (indicated by the shaded areas) it is repelled. The right-hand figure shows this in the form of a curve, the net pull being

represented by the difference between the areas above and below the horizontal line.

The B/H curve shown in Fig. 71 has, needless to say, been very much exaggerated for the sake of clearness, and in well-designed modern instruments the error is small. For example, in the case of a "Universal" ammeter (p. 141) Burrowes[1] found it to be too small to measure. In fact, it is possible to reduce the difference in reading between alternating and continuous current to a very small value (say, ½ per cent. of the reading) in all cases except voltmeters of low range where self-induction cannot well be eliminated. It was pointed out on p. 134 that the permeability of iron is slightly less, at low inductions, with alternating than with continuous current, which also has the effect of causing the instrument to read lower.

There is another manifestation of hysteresis which occurs in some instruments when used with continuous current, namely, the so-called **rotational hysteresis.** This is only found in those constructions in which the direction of the magnetic flux through the iron changes with the deflection. The lag due to this cause, sometimes known as "position error," can be determined by switching on about 70 per cent. of the full scale current and then allowing the pointer to come slowly up to its reading without any overshoot, by holding it back. Next, the current still flowing, the pointer is moved by hand to the top of the scale and allowed to come back slowly to its reading. The point of rest in the latter case will be higher up the scale than in the former, the difference between the two being a measure of the position error. In actual practice the effect is small, and is indistinguishable from that of hysteresis of the ordinary form.

Turning to **actual types,** only a few typical examples can be given. A well-known arrangement is shown diagrammatically in Fig. 72, and consists of a fixed rod of soft iron (A) and a moving iron (B). The coil has a winding giving some 400 ampere-turns at full current, and the two

[1] *Loc. cit.*, p. 135.

rods, being similarly magnetised, tend to repel one another. As has been shown, if the induction in the iron is kept fairly low, the force of repulsion at any point will be, roughly, proportional to the square of the current. As the needle deflects, however, the greater becomes the distance between the two rods, and the torque is not proportional to the square of the current flowing,[1] so that if the motion is opposed either by a spring or a weight (see p. 27) the scale may be fairly evenly divided from about one-fifth of the maximum reading upwards. A typical moving iron ammeter scale is given in Fig. 73, and while the lower part of the scale can be made somewhat more open than this, it is found impossible, in any moving iron instrument, to produce such

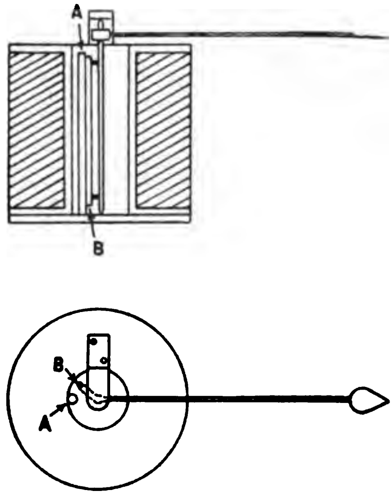


FIG. 72.—Repulsion Type Moving Iron Instrument.

FIG. 73.—Typical Moving Iron Ammeter Scale.

a scale as to give satisfactory readings below one-tenth of the maximum current. For this reason it is always a mis-

[1] Although this is the case, it does not follow that the instrument will not respond to the R.M.S. value. This latter property depends on the torque *at any given position* of the moving iron being proportional to the square of the current. It has nothing to do with how the torque varies for different positions of the iron.

take to select an ammeter with a higher maximum reading than is necessary.

Fig. 74 shows, diagrammatically, another system of moving iron instrument. The iron B is repelled by A towards its thinner end, and the shapes are determined, once for all, so as to yield a scale as evenly divided as possible.

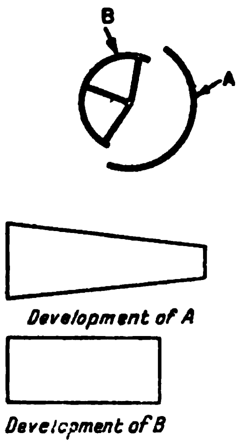


FIG. 74.—Repulsion Type Moving Iron Instrument.

In another form of instrument only one iron is used, and this is drawn into the coil. The force of attraction then depends upon the current flowing, but, unless special precautions are taken, the maximum deflection attainable will be small, owing to the rapidity with which the force falls off as the core is withdrawn. Fig. 75 shows this for a typical case. The height of the curve above the horizontal line represents the pull due to the solenoid for various positions of the centre of the core (shown by a dot) when a current is flowing

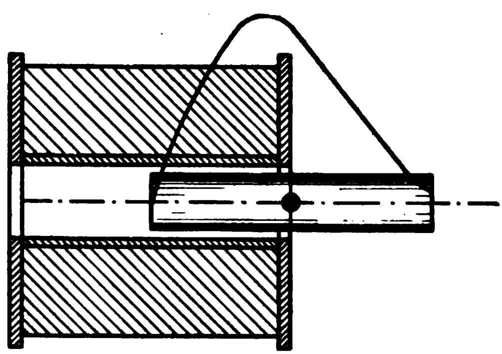


FIG. 75.—Pull due to a Solenoid.

through the coil. When the centre of the core coincides with that of the coil the pull is zero, and, as the core is withdrawn, the pull reaches a maximum and then falls off again. In order to make the curve less steep the core can

be shaped with a pointed inner end, but, no matter what precautions are taken, the scale obtained is an unsatisfactory one, and this form of instrument is but little used at the present time.

In the "Universal" ammeters and voltmeters of Everett-Edgcumbe only one iron is employed, but this takes the form of a flat disc (B, Fig. 76) of special shape. So soon as current is passed through the coil the iron is drawn in with a force depending upon the ampere-turns. The motion is, as usual, opposed either by a spring or weight, and the disc is so shaped that a comparatively evenly divided scale is obtained from one-fifth of the maximum reading upwards.

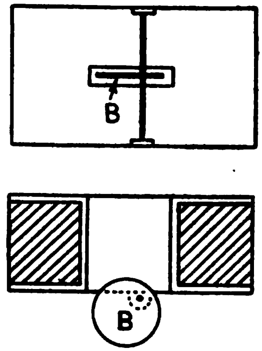


FIG. 76. — "Universal" Moving Iron Instrument.

The flat shape of coil has several advantages. In the first place, the winding can be brought very close up to the iron, whereby the working forces are increased. Secondly, the length of a turn can be kept small; and thus not only is the resistance kept down, but the self-induction is reduced to a minimum. This fact, coupled with a very low magnetic

FIG. 77.—"Universal" Voltmeter Scale.

induction in the iron, results in an almost negligible difference of reading between direct and alternating current, and eliminates the disturbing effects of both frequency and wave form (see pp. 135 and 138).

By setting the disc D round on the spindle, so that when the pointer is in the zero position it is further out of the coil,

it is possible to obtain an open scale, such as is shown in Fig. 77, which is particularly useful for voltmeters, since readings are usually wanted over a small range, only, on either side of the normal pressure.

For **central station** use **voltmeters with still more open scales** are required, since the accurate determination

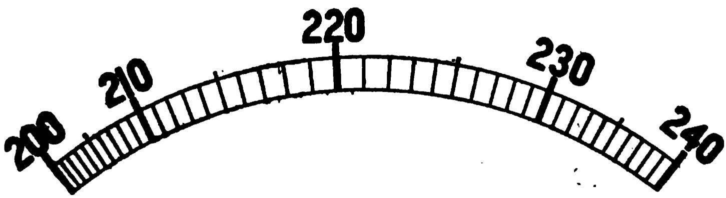


Fig. 78.—Specially Extended Alternating Current Voltmeter Scale.

of the bus-bar pressure from a distance is of importance. For continuous current a moving coil instrument (see p. 144) lends itself to the purpose, and for alternating current a special form of solenoid movement has been designed by

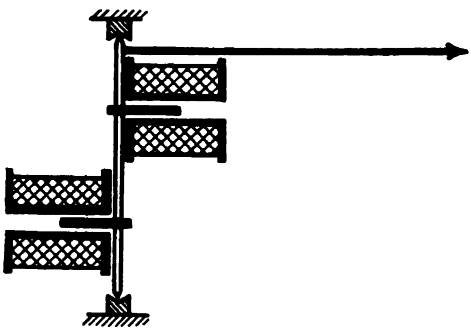


Fig. 79.—Astatic "Universal" Instrument.

Everett-Edgcumbe, which gives an extremely open scale (Fig. 78).

Many other forms of moving iron instruments have been introduced from time to time, but those described are typical of them all.

The "Universal" form of instrument can readily be made **astatic** (Fig. 79), so as to eliminate errors due to stray magnetic fields (see p. 12). Two similar coils are placed

one above the other, and so wound that their polarity is opposite. Thus any stray field strengthens one coil by the same amount that the other is weakened, so that the effect on the torque is negligible. Such an instrument, fitted in a cast-iron case, is perfectly free from stray field errors. The astatic principle is not so easily applied to other forms of moving iron instrument.

When **multi-range ammeters** are required, it is possible to use—(1) shunts, (2) two or more windings which can be connected in series or parallel, as required, (3) two or more separate windings on the same bobbin, or (4) current transformers. Of these the first is liable to contact errors, the resistance of the instrument being low, and with alternating current frequency errors are difficult to avoid. This is owing to the self-inductions of winding and shunt being different, unless special shunts of adjustable self-induction are used (p. 52). The second is limited in its application, since with two windings only two ranges are possible (ratio 1 : 2), or three ranges (ratio 1 : 2 : 4), with four windings. The third method is the most elastic, but since only a fraction of the whole winding space is available for each range, the working forces are apt to be somewhat low. The fourth method is preferable in most instances, but care is necessary in the design of the transformer (see p. 318). The best ratios in all cases are 1 : 5 : 25.

The chief **defects** to which moving iron instruments are liable are—(1) large **power consumption** as voltmeters (say, 5 to 10 watts at 200 volts); (2) **temperature error** in voltmeters (say, 0·3 per cent. to 1 per cent. fall per 10° C. increase of temperature). For this reason moving iron voltmeters are not to be recommended for maximum scale readings of less than, say, 10 volts. (3) Effect on the reading of **stray magnetic fields** due, for example, to neighbouring dynamos and motors, or to cables carrying heavy currents. A bus-bar some 3 ft. away carrying 1,000 amperes may well produce an error of 1·5 per cent. or more in an unshielded instrument. The error with a well-shielded instrument, however, should not exceed a quarter of this

amount, and with an astatic movement is quite negligible. It may be mentioned that if the + and − bars are near together their effect cancels out, to a large extent, and they can be brought nearer the instrument without danger (see also p. 12). (4) **Hysteresis errors** with continuous current, amounting to, say, 1 per cent. of the maximum reading. (5) **Frequency errors** in well-designed instruments are negligible at ordinary power circuit frequencies. For wireless work at, say, 400 periods per second they may be quite appreciable, unless the instruments are calibrated at or about the frequencies on which they are to be used. This applies more especially to voltmeters, owing to the relatively high self-induction of the winding. The difference in reading between 50 periods and 400 periods might well amount to 7 per cent. in a voltmeter and 2 per cent. in an ammeter. In the "Universal" pattern (p. 141), on the other hand, which is specially designed to reduce frequency errors to a minimum, the corresponding differences would be about 3 per cent. and ½ per cent. respectively. (6) Comparatively **low resistance of voltmeters and high resistance of ammeters** when used for ranges of less than, say, 10 volts and 1 ampere respectively.

Summing up the position, it may be said that for continuous current the moving iron instrument is much inferior to the moving coil pattern, but for alternating current it is superior to all types except the dynamometer and the electrostatic and even possesses many advantages as compared with these.

Moving Coil Ammeters and Voltmeters.

The principle on which these instruments are based was due originally to MM. Deprez and D'Arsonval, but the first really practical ammeters and voltmeters on this system were designed by **Weston** in America. Since then, improvements have continually been made, and there can be little doubt that for continuous current measurements the modern moving coil instrument is about as perfect as it well can be.

Fig. 80 shows a typical example in section. The air-gap

is reduced to a minimum (say, 1·5 mm., or less, on each side of the core) in order to obtain as strong and permanent a field as possible (see p. 57). The coil is wound on an aluminium or copper frame or "former," carrying a pivot at each end. When it swings in the magnetic field, eddy currents are induced in it which tend to oppose the motion and so to damp out the oscillations. To such an extent is this the case that a well-designed moving coil instrument of moderate dimensions is almost perfectly aperiodic (see p. 40).

Since permanence of calibration is dependent upon the **constancy of the magnet,** every possible care must be taken

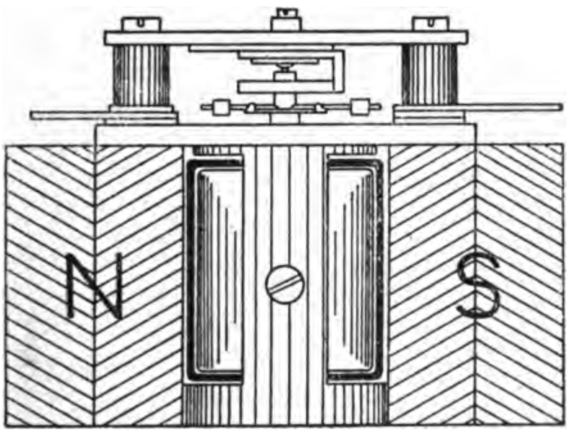


FIG. 80.—Typical Moving Coil Instrument.

in the selection and ageing of the steel, and the polar area should be made as large as possible, while the length of the air-gap is kept as short as possible. In fact, the ratio—

$$\frac{\text{length of magnet}}{\text{section of magnet}} \times \frac{\text{section of air-gap}}{\text{length of air-gap}}$$

should be as large as possible. It varies, usually, between 150 and 500, and in no case should it be less than 100 (see p. 65 for a further discussion of this question). The flux density in the air-gap ranges, as a rule, from 500 to 2,500 per square centimetre, and in the steel from 1,000 to 6,000.

The length of the air-gap being the same at all points,

the magnetic field is practically uniform, and since the torque is directly in proportion to the product of the magnetic density into the current flowing, the force at each point is proportional to that current. The motion is invariably controlled by one or two spiral springs (see p. 32), which often serve to lead the current into and out of the coil. The force exerted by a spring being proportional to the angle turned through, it follows that the deflection is proportional to the current, with the result that the scale is evenly divided throughout its length.

For many purposes, particularly in the case of voltmeters, it is of considerable importance to have a very **open scale** over the working range, the part below this being comparatively unimportant. This is easily arrived at by "setting up" the spring, so that the pointer only starts moving when a certain minimum current is flowing through the coil. The scale will still be evenly divided, and any required range can be obtained. The effect is, in fact, the same as if the instrument were provided with a scale, say, three times as long as is actually the case, but of which only the last third was visible. It must be remembered, however, that such an arrangement merely enables a more exact *reading* to be taken, and does not in any way increase the intrinsic accuracy of the instrument, in fact, rather the reverse. A "set-up" such that the suppressed portion is two-thirds of the maximum is the most that can be considered satisfactory. This would correspond, for example, to a scale reading from 100 to 150. A greater suppression than this is liable to lead to lack of torque, insufficient damping, and distortion of the spring (see p. 31).

For some purposes, the converse is aimed at; that is to say, a scale is desired which is very open over the lower part and closed up over the upper part. This can be obtained by arranging a second spiral spring, which only comes into action over the upper part of the scale (see p. 399 for a fuller discussion of this point).

It is evident that the amount of current which can be passed through the moving coil is extremely small, say half

an ampere at the most, and consequently "**shunts**" are used for heavier currents (see also p. 45). These shunts are usually constructed of a metal which has a negligible temperature coefficient, but, as the moving coil is invariably wound with copper or aluminium wire, its resistance depends greatly on temperature, and it follows that the proportion of the total current flowing through the moving coil will be greater the lower the **temperature,** and *vice versâ*.

To minimise this error, it is usual to connect in series with the moving coil a "swamping" resistance having a negligible temperature coefficient, so as to reduce the effective temperature coefficient of the moving coil circuit. A disadvantage of this arrangement is that an increased potential difference is necessary at the terminals of the shunt, in order to cause the requisite current to flow through the coil. This potential difference varies, as a rule, from 0·05 to 0·1 volt, 0·05 being a very usual value for extra-heavy current switchboard instruments, 0·075 for ordinary ranges, and 0·1 for standard testing instruments. The coil itself (including the springs or leading in ligaments) has usually a drop of potential at full deflection of from 0·04 volt in switchboard ammeters to 0·02 volt in standard instruments, so that the temperature coefficient ranges from perhaps 0·3 per cent. per degree Centigrade in the worst case of a very heavy current switchboard ammeter to, say, 0·05 per cent. in a standard instrument.

It might be thought that the **drop of potential** required at the terminals of the coil could be reduced by altering the winding, since it can be shown that for a given number of ampere-turns the potential difference is inversely proportional to the sectional area of the wire used (see p. 73). Theoretically this could be done, but in practice a limit is reached owing to the resistance of the springs or leading in ligaments and the leads[1] connecting the instrument to its shunt, which forms an increasingly large proportion of the total, and also to the fact that any decrease in internal resistance carries with it an increased chance of inaccuracy due to contact resistance.

[1] The resistance of the leads may be taken as about 0·05 ohm.

The resistance of the coil, usually, lies between 1 and 4 ohms.

The temperature coefficient of the springs or ligaments will vary from 0·1 per cent. to 0·4 per cent. per degree Centigrade (0·2 per cent. being a usual value), and it can be shown that the best results are obtained as regards temperature error when the resistances of the coil and springs are to one another in the inverse ratio of their respective temperature

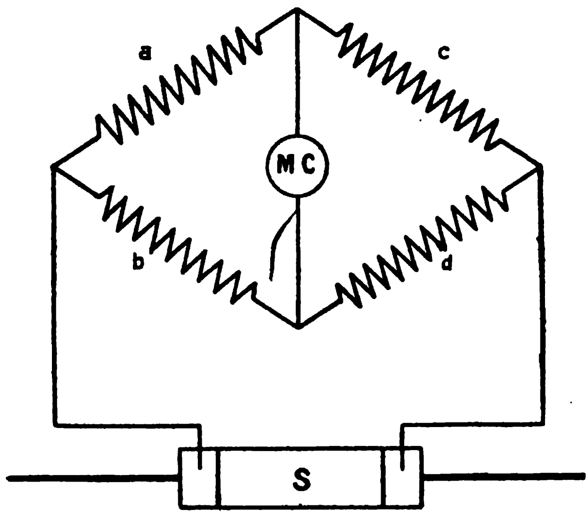


FIG. 81.—Campbell's Temperature Compensation for Moving Coil Ammeter.

coefficients. Theoretically the best results as regards torque for a given volt drop are obtained when the resistance of the winding is made equal to the idle resistance (*i.e.*, springs, leads, swamping resistance, etc.). But taking the temperature coefficient into account, it will be found best to make the resistance of the winding equal to about half that of the idle resistance. For a further discussion of this question see p. 33.

A device, due to Campbell, whereby almost perfect **compensation** is possible is shown in Fig. 81. The moving coil is represented by MC, and the shunt by S. The resistances *a*

and *d* are of copper or iron, while *b* and *c* are constructed of some material having a negligible temperature coefficient. It can be shown that if the coil MC has a resistance of 3 ohms, while the resistance of *b* and *c* is 1 ohm each and of *a* and *d* 3 ohms each, the compensation is almost perfect, and the fall of potential required at the terminals of the shunt need not, in practice, exceed 0·1 volt.

Fig. 82 shows another method of compensation. The moving coil C is connected to the terminals T, T, in series with two resistances, R_1 and R_2, of negligible temperature coefficient. C and R_1 are shunted by a third resistance (R_3) of copper. As the temperature rises the resistance of R_3 increases more than the combined resistance of C and R, and consequently a larger proportion of the total current

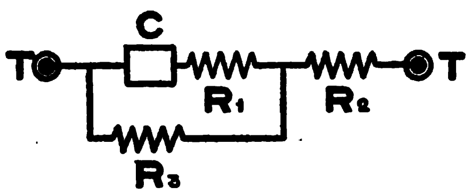


FIG. 82.—Temperature Compensation for Moving Coil Ammeter.

flows through the latter. By suitably choosing R_1, R_2, and R_3, almost perfect compensation can be obtained. It should be observed that neither this method nor that of Campbell is available for an instrument which is to be used both with a shunt as a milli-voltmeter and with a series resistance as a voltmeter.

An alternative method of compensation which has been suggested consists in shunting the magnet with a keeper of Guilleaume steel. In this material the permeability falls when it is heated. As the temperature rises, therefore, less and less of the flux is shunted, so that the density in the gap increases and, to some extent, compensates for the increased resistance of the winding. Unfortunately, the change of permeability with temperature is not large, so that without shunting the working flux to an excessive extent sufficient compensation cannot well be obtained.

When automatic temperature correction is not possible, either a known percentage can be added to the reading for each degree rise of temperature, or some semi-automatic adjustment can be provided. The simplest consists of a rheostat, graduated in degrees Centigrade and connected in series or parallel with the moving coil. Another device consists of an adjustable keeper to the magnet actuated by a cam which also carries a pointer moving over a scale graduated in temperatures or by a screw, as in p. 49.

It has frequently been suggested that if the shunt were made of the same material as the moving coil, the temperature error would disappear. This point of view presupposes either that the moving coil and shunt are not raised in temperature by the current flowing or that they become equally hot. Unfortunately neither of these conditions is fulfilled in practice, owing to the great disparity of cooling surface and heat capacity. It is, consequently, the universal practice to construct the shunt of a material having a negligible temperature coefficient, and to reduce the coefficient of the instrument itself by one of the methods already described.

Whatever form of compensation is adopted, it is important that the **contact resistance** should be reduced to a minimum. The resistance of the winding is only a few ohms, and there are four contacts (usually unsoldered) to be reckoned with, two in each shunt lead.

The limited space available for the **winding** must be filled as full of copper as possible. To this end, if round wire is used, it often becomes necessary to wind it in several layers, which can subsequently be connected in two or more parallels. Some makers employ wire of square or oblong section, or even wind the coil with round wire and afterwards place the coil in a press, whereby the wire is forced into shape without the silk covering being broken. To reduce the weight of the moving system, the coils are sometimes wound with aluminium wire, but the advantage of this is small.

It may be taken as a good working rule that to obtain the

best results as regards **ratio of torque to weight** (see p. 36) the weight of the active winding should be made equal to the "dead" weight of the other moving parts (pointer, former, balance weights, etc.).

The procedure to be followed in the **design of a moving coil instrument** is somewhat as follows :—

(1) Design former, pointer, etc., for minimum weight (let it be W gms.). Theoretically a square coil gives the best results for a given number of ampere turns.

(2) Calculate the torque necessary to ensure freedom from stickiness, assuming a total weight of 2W gms. It is shown on p. 36 that for a switchboard instrument this should not be less than $\frac{2W}{10} = \frac{W}{5}$ cm.-gms.

(3) Design suitable controlling springs (see p. 29).

(4) Calculate the winding so as to utilise the available space to the best advantage, bearing in mind that in the case of a voltmeter it is minimum current, and in that of an ammeter (milli-voltmeter) minimum over all pressure drop, which must be aimed at (see p. 69).

The design is in any case largely a matter of trial and error, particularly as regards the best dimensions of magnet and air-gap (see p. 63).

Whilst the movement illustrated in Fig. 80 is typical of the majority of moving coil instruments at present in use, departures from this pattern have been made in **various designs.** For example, in Everett-Edgcumbe instrument (see Fig. 83) the pivots E are fixed to the inner face of the moving coil D instead of to the outer, the jewels B being then set in the core (A). They are pressed outwards by

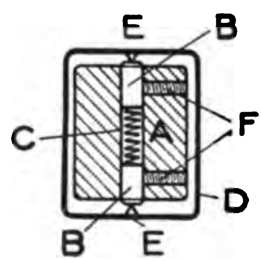


FIG. 83.—Internally Pivoted Moving Coil.

means of the spring C, and held in the correct position by the grub-screws F.

This arrangement has several features to recommend it, since, besides eliminating the jewel-carrying bridge, and thus leaving a clear space for the pointer, it gives a much more solid fixing for the pivots, which can be attached direct to the former instead of to the winding. Also, there is no fear

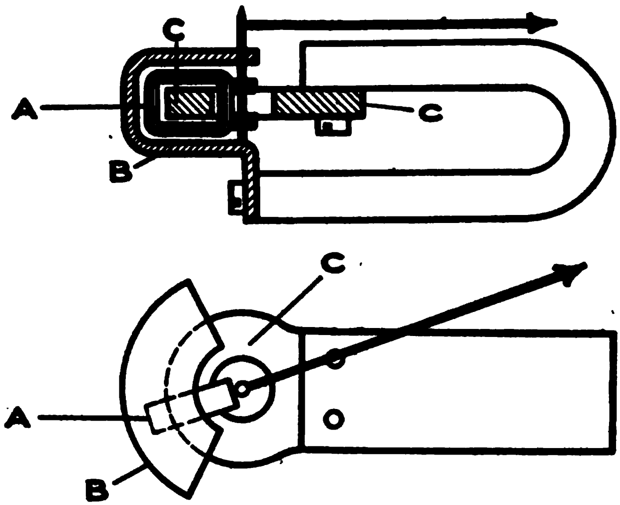


FIG. 84.—Special Form of Moving Coil Instrument.

of damaging the pivots through careless adjustment, since the maximum pressure on them is that due to the spring. Moreover, damage to the pivots, which is often caused by expansion with heat in other constructions, is prevented by the reduced distance between the pivot points, and by the fact that expansion draws the pivots back instead of forcing them on to the jewels.

Fig. 84 shows an American form of moving coil instrument in which an attempt has been made to increase the torque by surrounding three sides of the coil A by the pole piece. The latter (shown at B) consists of a specially stamped-up piece of soft iron attached to one pole of the permanent magnet. The core C is fixed to the other pole, and the

moving coil A swings in the gap between them. No advantage is actually gained, since it is impossible to ensure an even clearance all round, and consequently the air-gap has to be made abnormally wide.

More than twenty years ago Davis introduced a moving coil instrument in which the pole pieces were so arranged that a "**disc scale**" (see p. 24) subtending an angle of nearly 300° could be obtained. The arrangement is shown in Fig. 85, where A represents the coil, pivoted at B, and C the hollowed-out pole piece surrounding the core. These instruments were successfully developed, but at that time the demand was small, and the design was accordingly dropped until a few years ago, when it was revived by Record, who extended the pole pieces of the instrument shown in Fig. 84 so as to embrace an angle of nearly 300°.

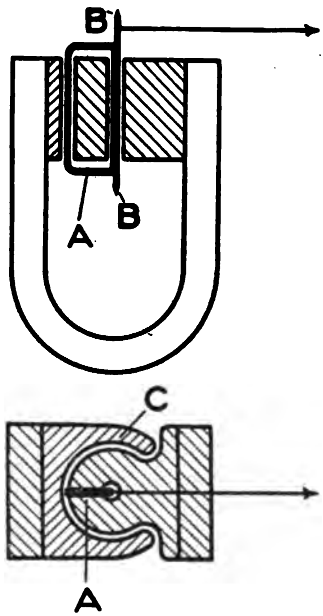


FIG. 85.—Davis Long Scale Moving Coil Instrument.

All such instruments, while giving a more open and more easily read scale, labour under the disadvantage that their intrinsic accuracy is not only no greater, but is actually less, owing to the increased travel for a given change of torque. This is, to some extent, compensated for by the reduced weight, owing to the shorter pointer for a given scale length, but to obtain satisfactory results it is necessary very largely to increase the strength of the permanent magnet; and, taking all things into account, it must be admitted that the advantage of a long scale is sentimental rather than actual, and while certain instruments, such as the induction pattern (see p. 166), lend themselves to it, the moving coil does not.

At the same time, where moving coil and induction instruments are mounted on the same board, the temptation to adopt a "disc" scale for both is a strong one.

A most important feature of all moving coil instruments lies in their **dead-beatness.** The copper or aluminium former, moving in a strong magnetic field, has eddy currents induced in it, which tend to oppose the motion (see p. 41). It is found that the ratio of $\frac{\text{torque}}{\text{weight}}$ (see pp. 36 and 39) bears a close relation to the damping. In practice this figure will range between 0·1 and 0·7 for round switchboard instruments, and a figure of less than 0·2 usually gives unsatisfactory damping.

Amongst the good points of a moving coil instrument one of considerable importance is the ease with which **a single instrument can be adapted to a number of measurements.** In the first place, although it is usual to wind a voltmeter with finer wire and more turns than an ammeter (*i.e.*, a milli-voltmeter), yet it is easy to find a winding which will serve both purposes. Such an instrument may take a current of 15 milli-ammeters as a voltmeter and require a drop of 75 milli-voltmeters as a shunted ammeter.

Various voltmeter ranges are obtained by means of a series resistance provided with appropriate tappings connected to separate terminals or, better, to a selector switch, and require no further remarks. The simplest arrangement for a multi-range ammeter consists of a number of independent shunts. For convenience the shunt blocks should be provided with sockets into which a pair of well-fitting plugs, attached to the terminals of the instrument, can be inserted.

A disadvantage of this arrangement lies in the fact that when changing from one range to another not only has the main circuit to be broken in order to insert a fresh shunt, but the plugs have to be changed over as well. One method of obviating this is illustrated in Fig. 86, which shows an instrument connected to three shunts for ranges of 4, 20, and 100 amperes, respectively. The main current enters at

the + terminal, and passes through either one, two, or three shunts in series, according to the position of the switch connected to the — terminal. The moving coil is joined to the outer ends, as shown, and the shunts are so proportioned that the drop of potential with 4 amperes passing through all three in series is slightly less than that obtained with 20 amperes through two, which is itself less than that with 100 amperes passing through one shunt. The reason that the drop has to be slightly less in each succeeding case is

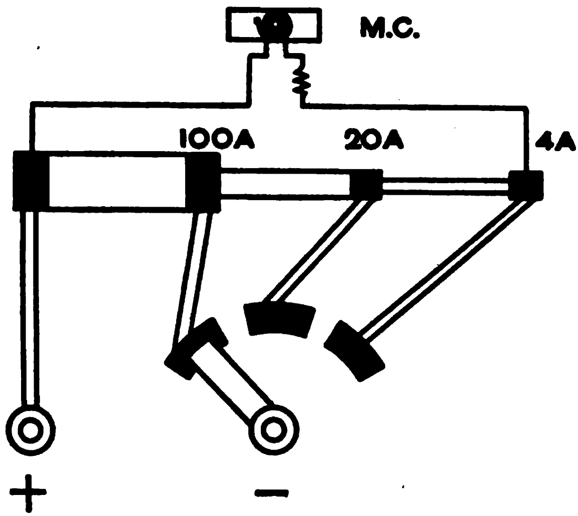


FIG. 86.—Three-range Moving Coil Ammeter.

that with the switch on the 100-ampere stop, for example, the other two shunts are in series with the moving coil, forming an additional swamping resistance, and consequently to obtain the same deflection with 4, 20, or 100 amperes the drop has to be progressively greater.

Another method of connection is shown in Fig. 87. In this case only one shunt is employed, having a fairly high drop at 100 amperes, and the moving coil is connected to it through two resistances which are successively cut out for the 20 and 4 amperes ranges.

By a combination of these two methods an extremely

wide range of currents can be covered with a comparatively small number of shunts. It may be added that similar methods are applicable to other instruments besides the moving coil, but owing to their sensitiveness, these latter lend themselves better than others to the construction of multi-range instruments.

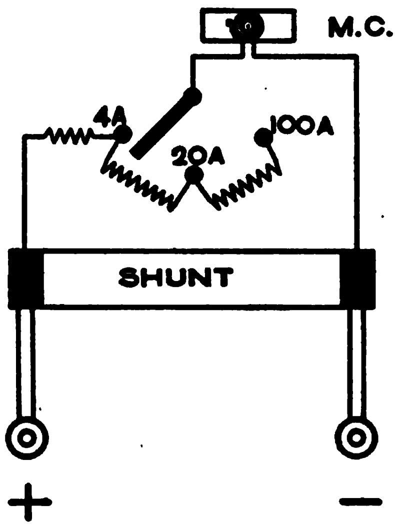


FIG. 87.—Three-range Moving Coil Ammeter.

Hot Wire Ammeters and Voltmeters.

If a current is passed through a resistance, the heat produced is proportional to the **square of the current,** and when once a steady temperature has been attained the heat generated must be equal to that radiated,[1] this latter quantity being proportional to the difference of temperature between the wire and the air surrounding it. Hence it follows that this difference of temperature is directly proportional to the square of the current. Such reasoning assumes that the resistance of the wire is independent of its temperature; but the effect of any departure from the "square law" due to this cause is, as a rule, small.

In "hot wire" instruments the rise of temperature of the wire is measured by its expansion. One of the earliest was the voltmeter due to **Major Cardew,** in which a wire of platinum silver ran twice up and down a long brass tube, passing over insulated rollers at each end. One extremity of the wire was fixed, while the other, after passing round a pulley geared to the pointer, was attached to a spring which kept it taut. The tube was made partly of iron and partly

[1] For a further discussion of this question see p. 376.

of brass, the proportions being so chosen that the coefficient of expansion of the tube was equal to that of the wire. Hence, so long as both were at the same temperature the readings were independent of external variations. These voltmeters were much used at one time, but dissipated a comparatively large amount of power (requiring nearly half an ampere) and have now given place to more modern instruments.

Of these a **typical construction** is shown diagrammatically in Fig. 88. The wire stretched between T_1 and T_2 carries the current to be measured. To its middle point (A) is attached a second wire, of phosphor-bronze, having its farther end rigidly fixed at B. A fine silk thread passes from C round the pulley attached to the pointer D, and is pulled taut by the spring E, which keeps the whole system in tension. By this means the expansion of the active wire is twice magnified, and the travel of the point C is some fifty times as great as the actual expansion of the wire.[1] An

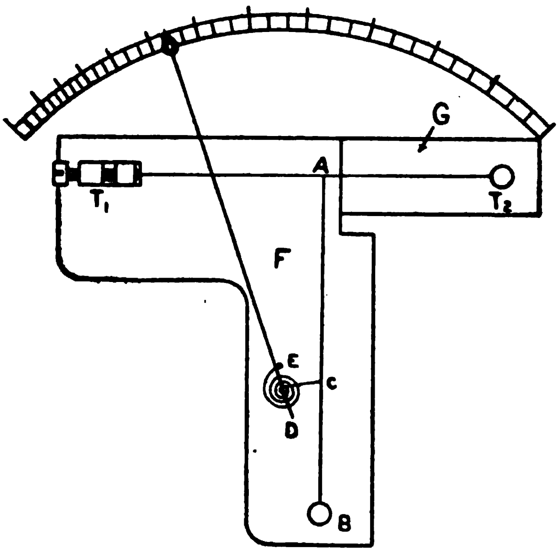


FIG. 88.—Hot Wire Voltmeter.

[1] The magnification does not approach the theoretical value owing to the stretching of the wire.

eddy current or pneumatic damper can be attached to the pointer spindle, if desired.

The base-plate F is of brass, and carries an extension (G) of iron, the proportions being so chosen as to give a net coefficient of expansion equal to that of the wire itself. Unfortunately, the wire reaches its final temperature almost instantly, whereas the base-plate requires a considerable time to do so, and hence on switching off after the instrument has been in circuit some little time the pointer seldom returns accurately to zero. For the same reason hot wire

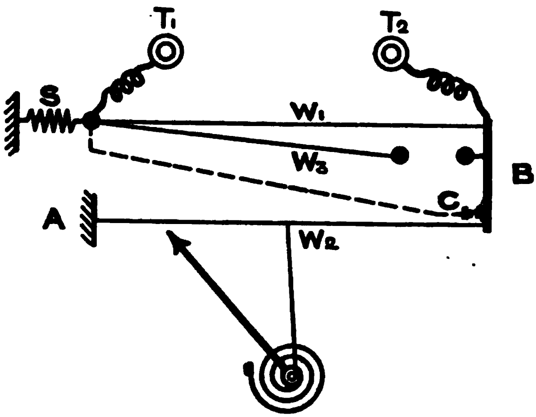


FIG. 89.—Hot Wire Voltmeter.

instruments, after being long in circuit, almost invariably read somewhat low. The adjusting screw shown at T_1 enables the zero to be corrected, but does not overcome the second trouble.

With a view to overcoming these defects, the arrangement shown in Fig. 89 has been used. The active wire is shown at W_1, and its expansion is transmitted through the bridge B, swinging on a knife edge, to the idle wire W_2, fixed at A, and thence, in the usual way, to the pointer. The current is led into W_1 from the terminals T_1 and T_2, and, instead of the other end of W_1 being rigidly fixed, it is attached to a spring, S, which pulls against a third wire, W_3. In this way so long as W_1 and W_3 expand equally—as will be the case under the

influence of changes of external temperature alone—the bridge B will remain stationary, but if W_1 expands under the influence of the current, the motion will be transmitted to the pointer. In practice, the expansion of W_3 must be slightly greater than that of W_1 to allow for that of W_2 as well. It would appear as though the compensation should be perfect, but such is, unfortunately, not the case, as, owing to gradual heating by the current itself and also to small differences in cooling, etc., creeping and loss of zero are unavoidable.

A more satisfactory method consists in **increasing the working temperature of the active wire** so that the differences of temperature dealt with are larger. This involves the use of a wire of higher melting point than the platinum silver previously used, and of which a number are now available (*e.g.*, platinum-iridium), and if this is done, considerable improvement in constancy is possible, without increased risk of damage through overloads (see below). Moreover, the wire is stronger, and so can be used thinner, with consequent reduction of sluggishness.

Owing to the danger of the wire burning out in the event of its being overloaded, and so leaving the secondary open-circuited, a hot wire ammeter working off a current transformer sometimes has a shunt taking a current at least equal to that of the instrument connected permanently across its terminals.

In order **to prevent sluggishness** of action, a fairly fine wire is essential, and this introduces a difficulty in the case of ammeters, which is usually overcome by passing the current through the wire in several parallels by means of thin silver strips making contact at different points along its length. Even by this means, however, it is found impossible to pass more than, say, 5 amperes through the wire, and a shunt is therefore employed. This entails a considerable **expenditure of power,** since a fall of potential along the shunt of from 0·15 to 0·5 volt (usually ·25 volt) is required. Even then, a large current is necessary, which renders the instrument very susceptible to contact errors. Voltmeters

usually require from one-third to one-tenth of an ampere to give a full deflection, some 3 to 5 volts being absorbed by the hot wire itself. It is evident that, other things being equal, a material of low specific resistance is best for ammeters and of high resistance for voltmeters.

In order to reduce the power absorbed in the case of a voltmeter, it has been proposed to overwind the active element by a fine insulated wire carrying the current, which may or may not pass through the active wire as well. This enables a much larger proportion of the total power to be usefully employed, but an accompanying disadvantage lies in the greatly increased heat capacity of the combination, which leads to sluggishness, a trouble against which the designer has always to be on his guard.

A disadvantage possessed by all hot wire instruments is their liability to be **rendered inaccurate, if not actually destroyed, by a comparatively small overload** (50 per cent. to 100 per cent.). As already mentioned, the wire is normally worked at as high a temperature as possible, so that the margin of permissible overload is small. Attempts to get over this trouble by means of fuses have not proved satisfactory, owing to the extreme rapidity with which the hot wire takes up its temperature. A more reliable arrangement consists in a mechanical cut-out worked by the expansion of the wire itself. Such a device is shown at C in Fig. 89. So soon as the expansion of the active wire exceeds that corresponding to full scale by, say, 30 per cent., the contacts C are closed, and the wire W_1 is instantly short-circuited through the connection shown dotted.

As has been seen, the extension of the wire is proportional to the square of the current flowing, and hence it follows that the **scales** of all hot wire instruments are considerably more open at the end than at the beginning. Whilst for a voltmeter which has, as a rule, a restricted range this is often an advantage, it is, at the same time, very undesirable in an ammeter, and attempts are sometimes made to improve the scale by means of levers, cams, and so forth.

Like other instruments following a "square law" (see

p. 10), hot wire ammeters and voltmeters can be used for either continuous or alternating current with equal accuracy; they are, moreover, unaffected by ordinary changes of frequency (see, however, next paragraph) or wave form and by stray magnetic fields. They are readily damped by means of a permanent magnet acting on an aluminium disc carried on the pointer spindle, should extra dead-beatness be required or the instrument be subject to excessive vibration. With these, practically all the advantages which can be claimed for hot wire instruments have been put forward, and against them must be set the serious disadvantages of change of zero, uncertainty of calibration, large power consumption, and liability to be destroyed by overloads. All things considered, therefore, it is hardly to be wondered at that for lighting and power work they have never been extensively used in this country, and that on the Continent their place is rapidly being taken by dead-beat moving iron or induction instruments.

When it was said in the last paragraph that a hot wire instrument was independent of frequency, this was strictly true only for frequencies up to a few thousand periods per second. When it is a question of **measuring the current in the aerial of a wireless sending station**, in which the frequency may amount to several million periods per second, the statement no longer holds good without qualification.[1]

A hot wire instrument will indicate, correctly, the current flowing through the wire itself no matter what may be the frequency, but should the instrument be used as a shunted ammeter, then the relative self-induction of the two circuits, although negligible at ordinary frequencies, becomes of importance. For example, a hot wire ammeter with internal shunt may show an error of 50 per cent. or more if connected in an areal.

The only way to eliminate this error is to make the self-induction of shunt and hot wire identical, that is to say, to arrange them symmetrically. Fig. 90 shows such an arrange-

[1] Wireless frequencies range as a rule from 100,000 to 1,500,000 periods per second.

ment; *s*, *s*, *s*, are narrow strips of a metal of high resistance and melting point attached, at either end, to circular brass blocks carrying, at their centres, terminals T_1 and T_2. To the centre of one of the strips is attached a phosphor-bronze wire, which magnifies the expansion and transmits it to a pointer in a similar manner to that shown in Fig. 89.

All the strips being identical as well as equidistant from each other and from the terminals, the induction of the various current paths is exactly the same, so that the distribution of current amongst them is independent of the frequency. An instrument constructed on these lines will

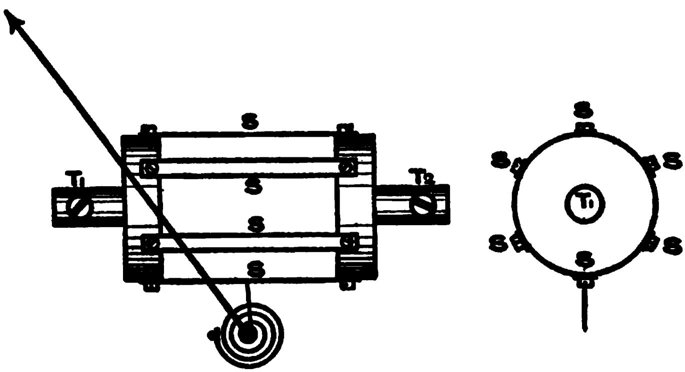


FIG. 90.—High Frequency Hot Wire Ammeter.

read correctly whether used with continuous current or connected in an aerial at a million cycles per second.

To ensure this, however, numerous precautions have to be taken. In the first place, it is essential that the ohmic resistances of all the conductors should be precisely the same. This follows from the fact that, as the strips are arranged symmetrically, the current will divide itself equally between them at high frequencies and must therefore be made to do so at low frequencies also, where the ohmic resistance is the determining factor.

Again, owing to the fact that the heat generated is proportional to the square of the current, the "skin effect," by increasing the current density in the outer portions of a

conductor, will produce a greater temperature rise with higher frequencies. It is clear that for a given size of conductor the effect will be greater the lower the specific resistance, and that, conversely, for a given material the effect is increased the greater the dimensions. For example, a copper wire 0·08 mm. in diameter shows an increase of 0·3 per cent. in resistance at a frequency of 1,000,000, whereas a Konstantan wire 0·05 mm. in diameter only shows an increase of 0·001 per cent. under similar conditions.

In certain cases the connecting leads may introduce errors; but if led out at right angles to the hot wires or strips (as is usually done in the case of switchboard instruments), or if kept in a line with them for some distance at either end, the error will be negligible. Eddy current effects need not be feared, so that metal cases are admissible.

It has been shown by Campbell and Dye[1] that current transformers can be used for increasing the range of thermal instruments, even on extra-high frequency circuits, provided the power consumption of the instrument is small. The primary of such transformers, which may be iron-cored, consists of one or two turns of carefully stranded cable, and the secondary of 100 or 200 turns of smaller wire, also carefully stranded. By this means currents of 50 amperes or more at frequencies up to 2,000,000 can be measured.

For radio-telegraphic work a hot wire ammeter scaled, not in amperes, but in watts expended in the instrument itself, is often used. Such an ammeter is generally called a "**watt indicator,**" but as this term is ambiguous, Brooks[2] has proposed the name "current-squared meter" as more appropriate, seeing that the scale reading is proportional to the square of the current. The ranges usually called for are quite low, seldom exceeding 0·1 watt, the current being something under 0·1 ampere.

The uses to which an instrument which reads the same with continuous as with alternating current can be put are so numerous that various attempts have been made to render

[1] *Electrician*, March 19th, 1915, p. 805.
[2] Circular No. 20 (2nd ed., 1915), Bureau of Standards (U.S.A.).

thermal instruments available for the **measurement of very much smaller currents and pressures** than the patterns so far described are capable of dealing with. The thermo-ammeter or voltmeter of Duddell is one such. It consists of a heating coil acting on a thermo-junction which, in its turn, sends a current through a moving coil instrument. At first sight this would appear to be a somewhat complicated arrangement, but by mounting the thermo-junction on the moving coil itself the instrument can be much simplified. Fig. 91 shows a voltmeter constructed on this principle. The ends of the moving coil, which has a single turn only, are brought out to a bismuth-antimony thermo-

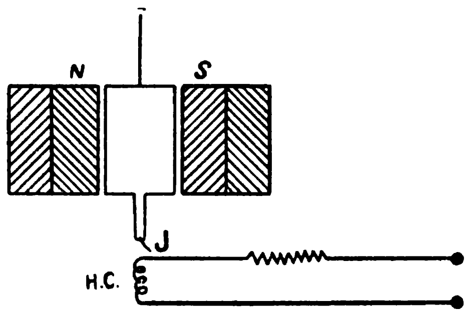


FIG. 91.—Duddell Thermo-ammeter.

junction, J. The heating coil HC consists of a platinum wire or strip wound non-inductively, or when extremely low currents are to be measured of a platinised quartz thread. It is possible, with a galvanometer constructed on this principle, to measure currents as small as a tenth of a milliampere, and it can be used indiscriminately for direct or alternating current of any frequency, so that it forms a very valuable instrument for many purposes where sensitiveness is sought, but extreme accuracy is not required.

Another arrangement which is simple in that a special moving coil instrument is not required is shown in Fig. 92. A copper wire is stretched between terminals T_1 and T_2, and one of Konstantan between T_3 and T_4. At their point of

intersection the two wires are soldered together. If a current is passed between T_1 and T_4, the junction becomes heated, and a thermo-E.M.F. is developed between the terminals T_2 and T_3 which can be connected to a galvanometer. For accurate work the junction is enclosed in an exhausted bulb, so as to protect it from draughts and from corrosion. When it is essential to separate the two circuits the heater can be kept out of contact with the thermo-junction, but if this is done the sensitiveness is reduced. With a heater of 1 ohm resistance currents down to 5 milliamperes or less can be read on a portable instrument, and very much lower currents

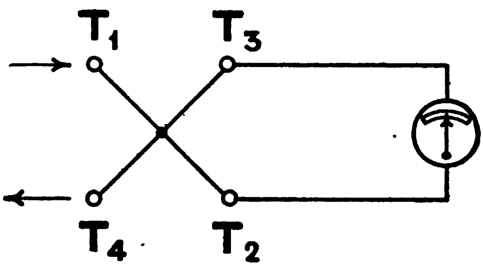


FIG. 92.—Srmple Thermo-ammeter.

on a reflecting galvanometer or by means of a potentiometer.

The self-induction of such instruments can be made negligibly small, so that they may be used for extra-high frequency testing. They are conveniently standardised with continuous current, but care must be taken in that case to eliminate reversal errors by changing over the connections. For the measurement of currents higher than the wire will carry, shunts can be used, but for extra-high frequencies various precautions have then to be taken (see p. 161). Fleming arranges a number of wires in parallel in the form of a squirrel cage, as in the ammeter shown in Fig. 90. To one of these wires the thermo-junction is connected, and so long as the arrangement is made symmetrical it can be used for continuous current, moderate, or extra-high frequencies with equal accuracy.

Induction Ammeters and Voltmeters.

It is of interest that Ferraris, to whose researches the induction motor is so largely due, was originally of opinion that the efficiency of such motors must necessarily be so low as to render them impracticable, and therefore devoted his attention primarily to the application of this principle to the construction of measuring instruments.

Induction ammeters and voltmeters fall into three classes :—

(1) The Ferraris or split circuit type.
(2) The divided pole or shielded type.
(3) The transformer type.

(1) In the simple **Ferraris** design the moving element consists of a thin cylinder of copper or aluminium surrounding a fixed core of laminated iron. Round the cylinder are four laminated poles, spaced 90° apart, with coils wound on them which carry the current to be measured. The coils are grouped in two pairs, so that the current in the pair on one diameter lags approximately 90 electrical degrees behind that in the pair on the other diameter, the arrangement being, in fact, similar to that of a two-phase induction motor. The phase difference between the two circuits is obtained by connecting them in parallel, making one of them as highly inductive as possible, while including considerable resistance in the other, so as to make it non-inductive.

This arrangement works well, although expensive to make, and is used to some extent, chiefly in the United States and in Germany.

(2) The divided or **shielded pole type,** due to Elihu Thomson rather than to Ferraris, is considerably simpler, and is illustrated in Fig. 93. The aluminium disc A, pivoted in jewels, passes between the poles of the electromagnet B, energised by the current to be measured. C, C, are short-circuited copper rings which enclose or "shield" rather more than half the polar area. When an alternating current is passed through the coil, the flux divides into two

components, which pass through the enclosed and unenclosed portions of the polar area, respectively. The former component lags behind the main or resultant flux on account of the eddy currents induced in the ring, while the latter leads somewhat. Thus the field in the gap may be considered as travelling continuously from the unshielded to the shielded portion, so producing a drag on the disc in this direction, which is opposed by the spring S.

Or, looked at from another point of view, the current in the disc induced by the lagging flux (Φ_2) reacts with the unlagged flux (Φ_1) to produce a torque proportional to the product of these two quantities into the cosine of the angle

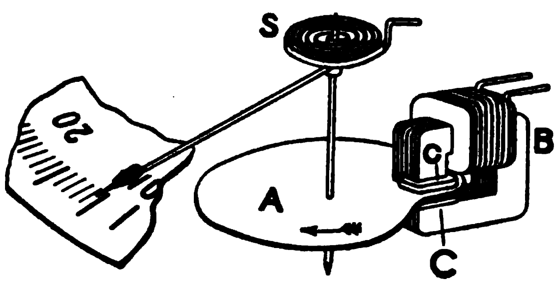


FIG. 93.—Shielded Pole Induction Ammeter.

between them. The current in the disc is proportional to $\frac{\Phi_2 . f}{R}$, where f is the frequency, and R the specific resistance of the material of the disc, so that —

$$\text{Torque} \propto \frac{f . \Phi_2 . \Phi_1 \times \cos \gamma}{R},$$

where γ is the angle between the flux Φ_1 and the current in the disc due to Φ_2. But if the self-induction in the disc can be neglected, the angle between the fluxes, $\theta = 90 - \gamma$, so that $\cos \gamma = \sin \theta$. Consequently, assuming the resistance of the disc to be constant:

$$\text{Torque} \propto f . \Phi_1 . \Phi_2 . \sin \theta.$$

An elementary vector diagram for an ammeter is given in Fig. 94.[1] The current flowing in the winding is represented by I. Owing to hysteresis and eddy currents, the flux Φ_1

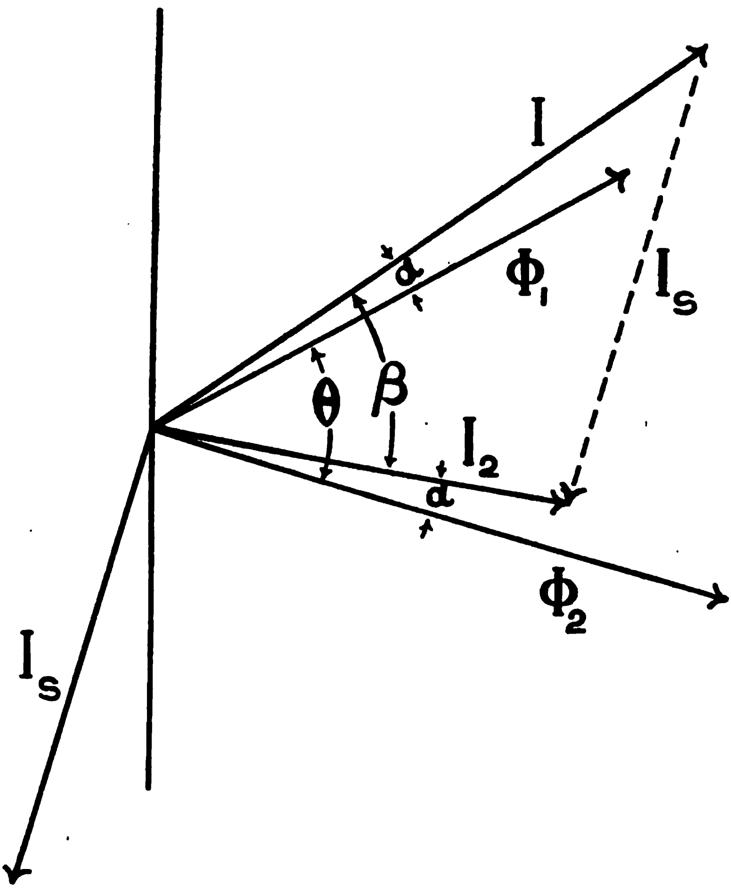


FIG. 94.—Vector Diagram for Shielded Pole Ammeter.

in the unshaded part of the core lags behind this current by a small angle, α. If Φ_2 represents the flux in the shaded por-

[1] For a more detailed discussion of the split phase magnet see F. Hymans, *Electrical World*, Vol. 68, pp. 1000 and 1192, also *Electrician*, Vol. 78, p. 638.

tion, the current in the shading ring C (Fig. 93) will lag nearly 90° behind Φ_2, and is represented in Fig. 94 by I_s. The M.M.F. producing the flux Φ_2 is the vectorial difference between the main current I and the secondary current I_s.

This difference is represented by I_2, and since the two portions of the magnetic circuit may be assumed to be similar, except for the shading ring on one of them, the flux Φ_2 will lag behind I_2 by approximately the same angle, α, as that by which Φ_1 lags behind I.

It has been seen that—

$$\text{Torque} \propto f \,.\, \Phi_1 \,.\, \Phi_2 \,.\, \sin\theta.$$

From Fig. 94 $I_s \propto I \,.\, \sin\beta \propto I \,.\, \sin\theta$, where β is the angle between I and I_2. But $I_s \propto \Phi_2 \,.\, f$, and therefore $\Phi_2 f \propto I \,.\, \sin\theta$. Since the air-gap is comparatively large, we may assume $\Phi_1 \propto I$ approximately, so that we have—

$$\text{Torque} \propto f \,.\, \Phi_1 \,.\, \Phi_2 \,.\, \sin\theta \propto I \,.\, \sin\theta \,.\, I \,.\, \sin\theta \propto I^2 \sin^2\theta.$$

Thus the torque is proportional to the square of the current, so that the scale follows a "square law," as in the case of most alternating current instruments.

If I (and therefore Φ_1) and f are constant, the torque will be a maximum when $\Phi_2 \,.\, \sin\theta$ is a maximum. But Φ_2 is proportional to I_2, and $\sin\theta = \frac{I_s}{I}$. Consequently the torque will be a maximum with $I_2 = I_s$, that is when β, and therefore θ, is 45°.

The **effect of a change of frequency** upon the torque with a given current is roughly as follows: If θ is small, I_2, and with it Φ_2, is independent of frequency. Hence we have torque $\propto I^2 \sin^2\theta \propto I_s^2 \propto (f \,.\, \Phi_2)^2 \propto f^2$. The hysteresis loss current is independent of frequency, but if the eddy current loss in the iron is considerable, α will increase with a rise of frequency. So long as the two parts of the core are magnetically similar, the two angles of lag will remain equal to one another, and θ will still be equal to β. Since the scale follows the "square law," as has been seen,

the change of reading is proportional to $\sqrt{\text{change of torque}}$, and is therefore directly proportional to the change of frequency.

If $\theta = 45°$, I_2 decreases as I_s increases, so that $I_2 \times I_s$ tends to be constant, and since torque $\propto I_s^2 \propto I_s \cdot I_2 \cdot f$, we have torque $\propto f$, or reading $\propto \sqrt{f}$. If the angle is still further increased, the effect of a given change of frequency becomes less and less. In practice it is difficult to obtain a large angle between the fluxes, particularly at low frequencies, so that it may be assumed that a change of x per cent. in the frequency will be accompanied by a change in the reading of at least $\frac{x}{2}$ per cent., unless some form of compensation (see p. 172) is adopted.

The effect of a change of temperature is to alter the resistance of both the disc and the shading ring, the currents in each being inversely proportional to the resistances. The effect of a change in resistance is the reverse of that due to a similar change of frequency. Consequently, an increase of x per cent. in resistance would be accompanied by a reduction of something over $\frac{x}{2}$ per cent. in the reading. Or, assuming a temperature coefficient of 0·44 per cent. per degree Centigrade (see p. 176), the temperature error would amount to nearly 0·3 per cent. per degree. (See p. 172, however, for methods of compensating for this.)

Fig. 95 gives the corresponding vector diagram for a voltmeter. The main flux Φ is divided, as before, into shaded and unshaded portions, Φ_1 and Φ_2, respectively. These fluxes lag behind their magnetising currents by a small angle, α. If I is the current flowing in the winding, I_2 can be found, as in the case of an ammeter. The flux Φ, linking with the winding, produces a back E.M.F., E and the impressed voltage has to overcome this E.M.F. and further to provide for the ohmic drop in the coil (IR). This drop is in phase with I, and the total impressed voltage is the resultant, represented by V.

If the frequency is constant, we have $\Phi \propto \frac{E}{f} \propto E$. But $I_s \propto f \,.\, I_2 \propto I_2$, and consequently β and θ are constant. Hence Φ_1 and Φ_2 are each of them $\propto \Phi \propto E$, and torque $\propto f \,.\, \Phi_1 \Phi_2 \,.\, sin\,\theta \propto \Phi_1 \,.\, \Phi_2 \propto E^2$. Moreover Φ_1 may be assumed to be approximately $\propto$ I, so that $I \propto E$ and $IR \propto E$; consequently $V \propto E$, and, as a result, torque $\propto$ V^2.

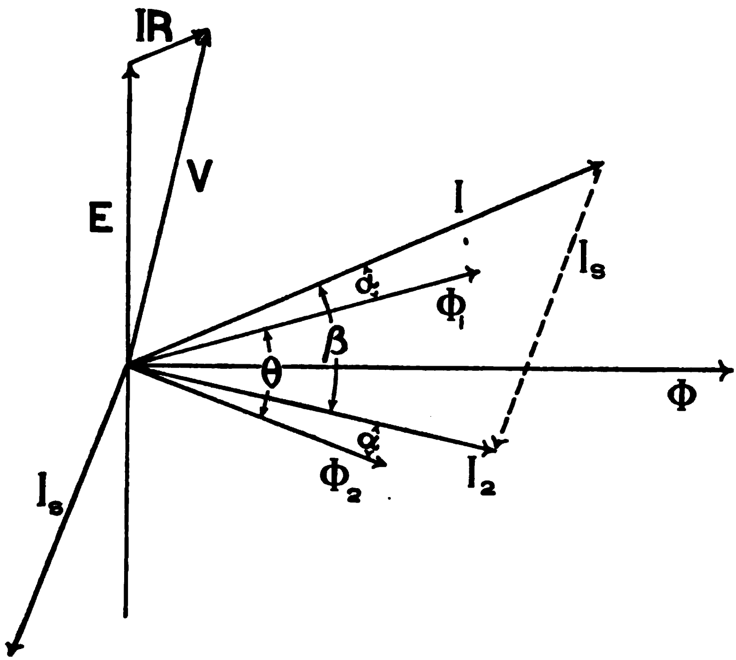


FIG. 95.—Vector Diagram for Shielded Pole Voltmeter.

As regards the effect of frequency upon the readings, if IR is small, E is constant, for a given value of V, and consequently $f \,.\, \Phi$ is also constant. From this it follows that the current I, instead of being independent of the frequency, as in the case of the ammeter, is an inverse function of it. As a result, the **effect of a given change of frequency** is very much less in the case of a voltmeter than

in that of an ammeter. In fact, if the pressure is applied directly to the winding without any swamping resistance, so that IR is negligible, the error due to small changes of frequency can be made negligible also.

On the other hand, the effect of a **change in the resistance** of the disc and shading ring **due to temperature** is the same as for an ammeter, and in order to reduce it recourse is had to one of the methods described below. These entail the addition of a swamping resistance, in consequence of which IR can no longer be neglected, and the effect of changes of frequency upon the readings is increased.

In an ammeter the **effect of frequency variation may be much reduced** by connecting a non-inductive shunt across the terminals of the instrument. A rise in frequency causes a reduction in the proportion of current taken by the inductive winding as compared with that in the non-inductive shunt, so that the torque tends to remain constant. This shunting device can also be made useful in reducing the temperature coefficient of the instrument in the way described later. The shunt is usually so proportioned that the current taken by the coil is about 75 per cent. of the total, and the reading is then affected by frequency to only about half the normal extent. For example, an unshunted ammeter may show an error of 0·8 per cent. for a 1 per cent. change of frequency, whereas if shunted the error would probably not exceed 0·4 per cent.

In the case of voltmeters, if the instrument is wound so that the winding absorbs the whole voltage, the readings are nearly independent of frequency, as has been shown. This arrangement, however, is subject to considerable temperature errors, so that some combination of shunt and series resistances is usually adopted as described on p. 176, and the instrument is not then entirely independent of changes of frequency.

(3) The **transformer type** of induction instrument, the most recently developed device, is in reality a refined form of the shielded pole pattern, just described. The electrical circuits of this instrument are shown diagrammatically

in Fig. 96. A laminated iron core carries the winding M, arranged to take the current to be measured, while A is a secondary winding, connected to an auxiliary coil, B, wound on the same core, but spaced half a pole-pitch from M and A with reference to the periphery of the drum or disc D. The arrangement of these electrical and magnetic circuits may be clearer from a reference to the instrument as developed by **Conrad.** This is illustrated in Fig. 97, the lettering corresponding to that of Fig. 96. The rotor consists of an aluminium drum, within which is a laminated

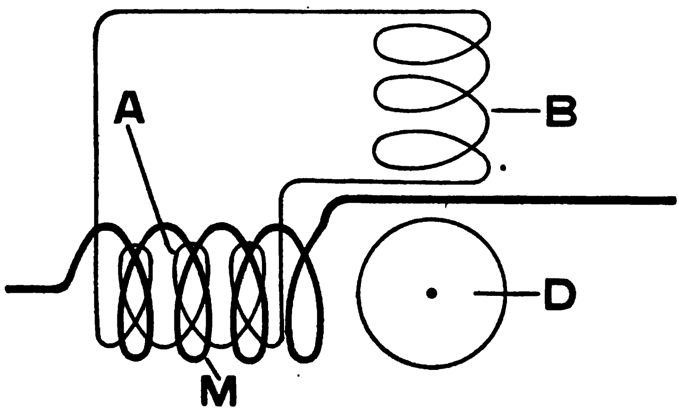


FIG. 96.—Transformer Pattern Induction Instrument.

iron core, C, so as to reduce the air-gap to the smallest possible dimensions.

Referring to the current transformer vector diagram on p. 319 (Fig. 194), it will be seen that the currents in the windings M and A (Figs. 96 and 97) must be nearly 180° out of phase, and that the flux in the core is nearly at right angles to both primary and secondary currents, so that the main flux is practically in quadrature with the main current. Now the secondary current from A in passing through the coil B produces another flux which is nearly in phase with this current, and therefore in quadrature with the flux in the part of the core surrounded by M and A. In direction this auxiliary flux is perpendicular to the main

flux and the combination of the two results in a rotating field which induces eddy currents in the rotor and thus creates a turning moment. The control takes the form of a spiral spring, in the usual manner.

The compensation of this instrument for changes of temperature depends upon the fact that an increase in the resistance of the auxiliary winding is accompanied by an increased flux through the transformer part of the core. Hence, if the windings are of copper, a rise of temperature automatically produces an increased operating flux, which counterbalances the effect of the increased rotor resistance due to the same cause. This compensation is so effective that it is usually found advisable to reduce the temperature coefficient of the secondary circuit by the addition of a resistance (R) of low temperature coefficient. The instrument then becomes nearly independent of temperature.

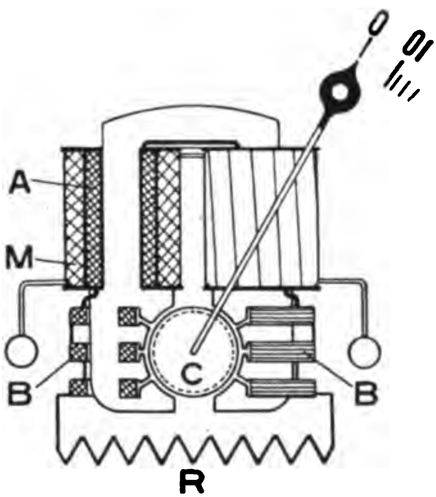


FIG. 97.—Transformer Pattern Induction Instrument.

Another advantage of this design is that by suitably adjusting the ratio of inductance to resistance in the secondary circuit the instrument may be rendered almost independent of frequency changes. Thus, for example, an ammeter may be adjusted so as to be correct at both 25 and 60 periods per second and not more than 1 per cent. out at any intermediate frequency.

The design illustrated in Fig. 97 has the disadvantage that the scale follows approximately a square law and is

therefore only readable with reasonable accuracy from about one-third scale upwards. As the entire periphery of the drum is surrounded by the magnet, the device described in the next paragraph is not applicable.

The motion in the case of both ammeters and voltmeters is usually controlled by a spiral spring, as shown at S, Fig. 93, so that, as has been said, the angle turned through tends to be proportional to the square of the current. In order to obtain a more uniform scale, the disc A is often made with a spiral outline, as illustrated in Fig. 93.

In another device a circular disc is used, but the control is arranged to increase faster than the deflection, for example by a combination of weight and spring control, so arranged that the weight assists the motion of the pointer in the lower part of the scale, but retards it in the upper part. This arrangement is only applicable to instruments with a 90° scale. In ammeters advantage may also, occasionally, be taken of the saturation of the iron core in closing up the divisions at the upper part of the scale.

Induction instruments lend themselves well to a construction employing a circular or " disc " scale, and are usually so constructed (see also p. 24). This affords a clear and easily read scale, but at the same time, owing to their large frequency and temperature errors, induction ammeters and voltmeters should not be employed when accuracy is important.

Damping can be effectively carried out by a permanent magnet acting on the working disc A, preferably in a position diametrically opposite to that of the electro-magnet B (Fig. 93), so as to minimise demagnetisation by the alternating current.

It was shown on p. 42 that there is a particular **position of magnet pole** which gives the greatest torque on a rotating disc. In the same way, there is a best position for the electro-magnet of an induction instrument. It is usually such that the centre of the magnet lies about three-quarters of the way from the centre of the disc to the periphery. If put nearer to the centre, the torque decreases, owing to the reduced

radius, and if nearer the periphery, the apparent resistance of the disc increases, owing to a crowding together of the current filaments.

The chief cause of **temperature errors** in induction instruments lies in the use of aluminium for the disc. In order to keep the weight on the pivots within reasonable limits, it is imperative that the disc should be made of the lightest possible metal consistent with reasonable conductivity, so that aluminium, with its comparatively high temperature coefficient, is unavoidable. To compensate for this, shunting resistances, when used, are generally constructed of a material having a high temperature coefficient, such as nickel or iron, so that, when the temperature rises, an increased proportion of the total current passes through the winding. The following are the temperature coefficients[1] of the materials most used :—

Copper	0·416 per cent. per degree C.
Aluminium . . .	0·438 ,, ,, ,,
Nickel	0·615 ,, ,, ,,
Iron	0·628 ,, ,, ,,

For induction voltmeters a form of Wheatstone bridge connection, similar to that described on p. 148, may be employed to reduce the temperature coefficient. A simpler device consists in using a shunt of high temperature coefficient and adding a series resistance of negligible temperature coefficient, or else an inductance, or a combination of the two.

The following indicates what may be expected from good switchboard instruments of the **shielded pole type** :—

—	Change of Reading due to 1 per cent. Change of Frequency.	Change of Reading due to each 1° C. Change of Temperature.
Voltmeter . .	0·1 per cent. (+)	0·15 per cent. (—)
Ammeter . .	0·4 ,, (+)	0·15 ,, (—)

[1] Results obtained by Fleming and Dewar, average values between 0° and 100° C.

These instruments are also subject to slight errors due to self-heating. The variation in reading due to this should not exceed 1 per cent. during a period of three hours from the time of switching on. The deflection usually increases during the first half-hour, owing to more rapid heating of the shunt, and then slowly falls to its original value after about an hour and a half. At the end of three hours the reading should be constant, but slightly low.

Dynamometer Ammeters and Voltmeters.

Instruments of the dynamometer class may be applied to the measurement of current or pressure by connecting the fixed and movable coils in series or parallel (see p. 181). With a **deflectional dynamometer ammeter** the current through the pivoted coil is limited to that which can be carried by the ligaments or springs, so that for currents of more than 2 or $2\frac{1}{2}$ amperes it becomes necessary to shunt the moving coil. In order to minimise the voltage drop over the instrument, the fixed coils are generally connected in parallel with the moving coil and thus constitute the shunt.

Unfortunately, by the adoption of parallel circuits the inherent accuracy of the dynamometer principle is sacrificed, and errors may be introduced due to any of the following causes :—

(1) The ratio of self-induction to resistance may differ for the two circuits, resulting in change of current distribution between them when the frequency is altered.[1] This can be overcome by increasing the resistance of one of the circuits until the time constant (*i.e.*, inductance/resistance) is the same for both.

(2) When working on an alternating circuit, currents are generated in the moving coil, owing to

[1] If M_C is the multiplying constant with continuous current, and M_A with alternating current,

$$M_A = M_C \sqrt{1 + kf^2},$$

where f is the frequency and k a constant (Drysdale, *Phil. Mag.*, Vol. 16, p. 138).

"transformer action." These induced currents react on the field, and produce a torque in such a direction that the moving coil tends to set itself in a plane parallel to that of the fixed coils, thus causing the instrument to read low over the lower and high over the upper part of the scale. This error cannot entirely be obviated, but may be minimised by adding non-inductive resistance to the moving coil circuit.[1]

(3) Temperature errors may be introduced, owing to differences in the proportion of copper resistance to total resistance in the moving and fixed coil circuits, thus causing a variation in the proportions in which the current divides between these two circuits.

(4) Creep may similarly be introduced, owing to the fixed and moving coil circuits being heated by the current at different rates or to a different extent.

The foregoing considerations point to the employment of a swamping resistance in both moving (MC) and fixed (C_1 C_2) coil circuits, as shown at r and R in Fig. 98. The moving coil is usually arranged to drop about one half the overall voltage, while sufficient resistance (R) is added to the fixed coil circuit to produce the correct division of current between the two. For heavy current windings, therefore, it will be found that a much larger proportion of swamping resistance (R) is required in the fixed coil circuit than for low current windings, since the ratio of resistance to inductance is inversely proportional to the sectional area of the conductor (see under Choking Coils, p. 77, for further details).

For small currents (say from 3 to 10 amperes) the arrangement shown in Fig. 99 is sometimes employed. In this case the moving coil circuit is shunted across a part only of the main winding, since the voltage drop over the

[1] See also p. 218.

whole may be more than is necessary for the moving coil, and, as a swamping resistance (R) has to be added, the drop would become unnecessarily large. With care in the selection of R and *r*, it is possible to design such a dynamometer ammeter for any ordinary range so as to be comparatively free from both temperature and frequency errors.

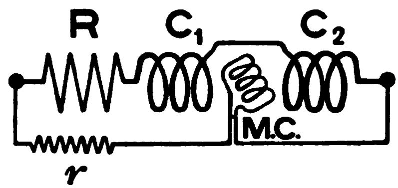


FIG. 98.—Dynamometer Ammeter.

Dynamometer voltmeters are simply low current ammeters with a considerable non-inductive resistance in series. Parallel paths being unnecessary, these instruments are free from most of the errors already enumerated, but are not necessarily independent of frequency or temperature in view of the possible inductance and temperature coefficient of the winding. For pressures above 100 volts, however, dynamometer voltmeters are but little affected, and may be employed without special calibration at all temperatures and at any frequency likely to be met with on power or lighting circuits. They possess the advantage, as

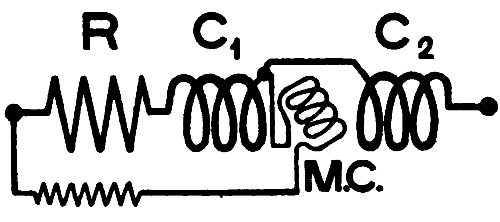


FIG. 99.—Dynamometer Ammeter.

compared with moving iron instruments, that no hysteresis error is introduced when employed on continuous current circuits.

In the case of portable instruments a **double range** is frequently desirable. This can readily be arranged in a voltmeter by means of a series resistance. In an ammeter, how-

ever, the matter is not quite so simple. For obvious reasons it is unsatisfactory to employ shunts, and it is usual to obtain two ranges by altering the internal connections. Fig. 100 shows one method of doing this, supposing the two ranges to be 5 amperes and 20 amperes respectively. The fixed current winding is divided into two parts, CC_5 and CC_{20}. For the 20-ampere range the terminals marked T and 20^a are used and for 5 amperes T and 5^a. Since, when using the 20-ampere winding, the drop is less than with the 5-ampere (see

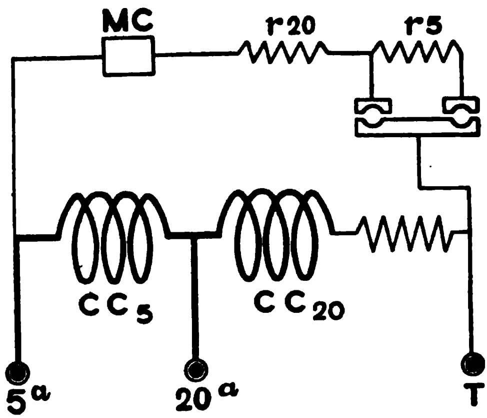


FIG. 100.—Double Range Dynamometer Ammeter.

above), a portion of the series resistance (r_5) can be cut out by means of a plug when the 20-ampere terminals are in use.

Such an arrangement is unsatisfactory in that only half the winding space on the current coil is utilised, so that the working forces are seriously weakened, and a series-parallel grouping is much to be preferred. Such a design, in its simplest form, gives a ratio of 2 : 1 between the ranges, but the modification shown in Fig. 101 enables a ratio of 1 : 4, or in the case considered, say, 5 and 20 amperes, to be obtained, which is a very great advantage. The two current coils are shown by CC, and the moving coil by MC. The former are connected through equal resistances, RR, to screw-down terminals, capable of being

joined in series by a single link, as shown, or in parallel by a pair of links, as indicated by the dotted lines. Supposing each of the current coils CC to be capable of carrying 10 amperes with a drop of 0·25 volt, then the drop with 20 amperes flowing and the coils in parallel will be 0·25 volt at the terminals of the moving coil circuit. When connected in series, with 10 amperes flowing, the drop will be 0·5 volt instead of 0·25, so that the current must be reduced in order to give the same deflection as before. By arranging a resistance (R_1), which can be plugged in or out of the moving coil circuit, matters can be so adjusted that

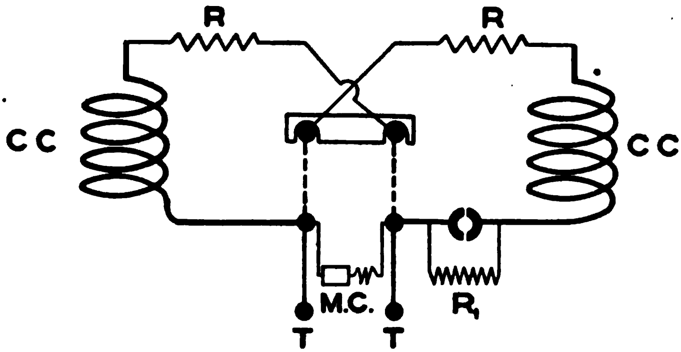


FIG. 101.—Double Range Dynamometer Ammeter.

a current of 5 amperes, with the coils in series, gives the same deflection as one of 20 amperes, with the coils in parallel. Such a ratio of 4 : 1 is most convenient for an instrument having a scale which closes up considerably at the lower end, as is the case with the deflectional dynamometer.

The **torque exerted between the fixed and moving coils** varies as the product of the currents in the two coils and roughly as the cosine of the angle by which the moving coil is deflected from the position of maximum torque (*i.e.*, when the axes of the fixed and moving coils are at right angles).[1] Now, since both moving and fixed coils carry the

[1] The cosine law is not strictly correct, since the torque also depends on the shape of the coils as affecting the uniformity of the field.

same current (or proportional currents in the case of shunted ammeters), it follows that the torque is proportional to the square of the current multiplied by the cosine of the angle, as just defined. Assuming spring control (in which the torque is proportional to the deflection from zero), the first factor (square law) would result in a scale in which the divisions steadily increase in length from zero to the upper limit of the scale. The second factor (cosine law) produces

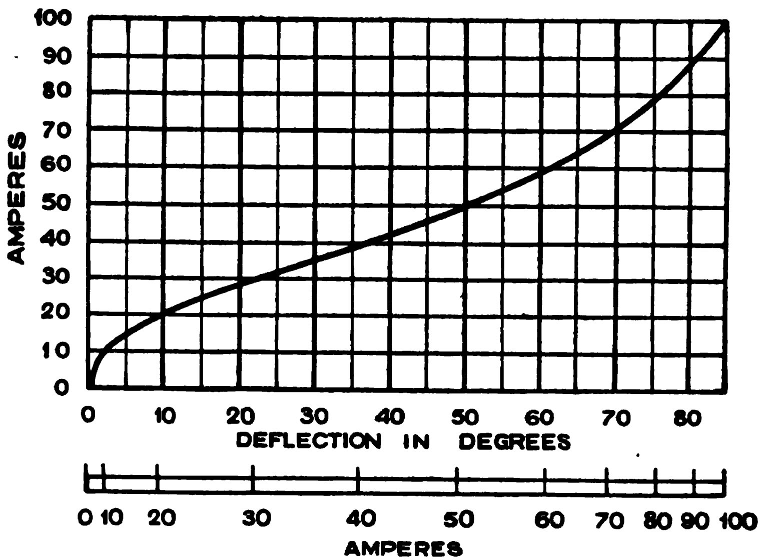


FIG. 102.—Predetermination of Dynamometer Ammeter Scale.

a scale with open divisions in the region in which the coils are at right angles to each other, beoming more cramped the further the moving coil is deflected from that position. The most uniform scale is obtained, therefore, by arranging the fixed and moving coils at such an angle to each other, when in the zero position, that the two factors tend to compensate over the working part of the scale. This is the arrangement usually considered most desirable in the case of an ammeter, and is illustrated by a graphic construction in Fig. 102. In this case the scale length is taken as 85°,

and the moving coil is assumed to pass through a position at right angles to the fixed coil at a deflection of 15° from zero. Where an open scale is required, as for a voltmeter, the angle through which the moving coil turns before reaching the position at right angles to the fixed coils may advantageously be increased to 30° or 40°.

The actual scale obtained in any given case is modified to a certain extent by the shape of the coils, and is generally somewhat more open at the ends than that obtained on the assumption of a cosine law for the torque.

Electrostatic Voltmeters.

The electrostatic system may be directly applied to the measurement of pressures and, with auxiliary resistances or transformers, to current and power also.[1] The indirect applications are, however, mainly of laboratory interest, and are not dealt with here.

Electrostatic voltmeters depend for their action upon the fact that an attraction is experienced by any two bodies between which there exists a difference of potential. The force of attraction is directly proportional to the square of the difference of potential between the bodies and to the exposed area and inversely proportional to the distance between the surfaces. It is also directly proportional to the dielectric constant or specific inductive capacity of the intervening medium. Taking the simple case of two parallel planes working in air, each with an area of A sq. cms. at a distance of d cms. apart, and supposing the potential difference to be V volts, the force of attraction between the planes is—

$$\text{Force} = \frac{V^2A}{8\pi d} \times \frac{10^6}{9} \text{ dynes}$$

$$\text{or } \frac{V^2A}{8\pi d} \times \frac{10^6}{9} \times \frac{1}{981} \text{ gms.}$$

If the planes are immersed in oil or some other medium of higher specific inductive capacity, the force is increased in proportion to the inductive capacity of the medium.

[1] See also p. 235.

From this expression it is easy to show that the working forces in an electrostatic voltmeter must be small compared with the weight of the suspended parts, particularly for low voltage instruments. In fact, it is not practicable to construct a voltmeter of this type for switchboard work which will operate in a satisfactory way on less than about 80 volts for full scale deflection.

It will be observed from the above expression that the methods available for increasing the working forces are—

(1) To increase the area (A) of the planes.
(2) To decrease the distance (d) between the planes.
(3) To use a fluid dielectric of high specific inductive capacity.

Method (1) involves also an increase in weight, and is therefore only useful up to the point above which the weight increases as rapidly as the force. Method (2) compensates, to some extent, for the fact that the force is proportional to the square of the voltage, since a low voltage instrument may safely be constructed with the vanes much closer together than one for a high voltage. In any instrument, therefore, the **distance between the fixed and moving vanes** should be reduced to a minimum compatible with safety, and the following table may serve as a guide in this respect :—

Working Pressure.	Minimum satisfactory Gap between Vanes.
2,000 volts.	0·2 inches.
4,000 "	0·35 "
6,000 "	0·5 "
10,000 "	1·0 "
15,000 "	1·5 "
20,000 "	2·0 "
40,000 "	3·0 "
80,000 "	6·0 "
120,000 "	9·0 "
200,000 "	15·0 "

The assumption has been made in drawing up this table that breakdown will occur between the edge of one plane and the surface of the other, thus corresponding roughly to a point and plane. For pressures of 20,000 and over the edges of the planes should be doubled over and rounded in such a way that breakdown will not occur from the edges. It is difficult to give reliable figures for the breakdown pressure between surfaces of this form, but the distances given in the table may be considered as safe.

Below 2,000 volts mechanical considerations in the design of the instrument become of primary importance in determining the length of the air-gap, and it is very seldom that gaps of less than 0·1 in. can be employed.

For pressures ranging from 50 to 8,000 volts the usual design of electrostatic voltmeter closely follows that of the quadrant electrometer originally suggested by Kelvin. Such an instrument may be connected in two ways, namely, **heterostatically** or idiostatically, as shown in Figs. 103 and 104 respectively. The former arrangement is mainly of use for measuring small pressures which are applied between the two fixed vanes or quadrants, as at V_2. A much higher voltage (V_1) is applied between the moving vane and one of the fixed vanes, this voltage remaining constant after the instrument has once been calibrated. Such an arrangement produces a force on the moving vane which is proportional, at any instant, to the voltage V_2. It will be seen that this method of connection is extremely inconvenient for switchboard voltmeters on account of the necessity for a constant exciting voltage (V_1), and it is not, therefore, employed for this purpose.

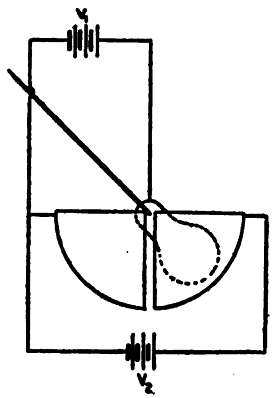


FIG. 103.—Heterostatic Connection of Electrostatic Voltmeter.

Slightly modified, however, the heterostatic principle may

be employed for power measurement[1] by making V_1 the pressure across the "load" and V_2 the voltage drop over a shunt. This arrangement is applicable to both continuous and alternating current work, and in the latter case takes account of the phase angle between the pressure and current in the circuit. A wattmeter of this type must be calibrated, however, at approximately the voltage at which it is to be used.

The connections commonly employed for measuring voltage correspond to the **idiostatic** method, illustrated in Fig. 104. In this case, the force of attraction at any instant between the left-hand fixed vane and the moving vane or "needle" is proportional to the square of the applied voltage V_2. The instrument therefore indicates the correct R.M.S. value of this pressure, whether it be continuous or alternating, and of any wave form or frequency.

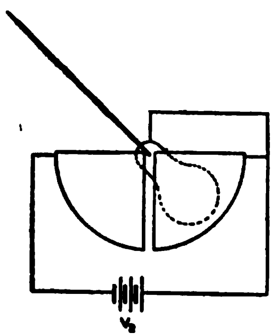


FIG. 104.—Idiostatic Connection of Electrostatic Voltmeter.

It will be observed that there is no force exerted between the right-hand fixed vane and the needle, since these are at the same potential, and it is possible therefore to discard the right-hand vane altogether. In order, however, to avoid the effects of stray electrostatic fields due to other masses in the neighbourhood (which may be at a different potential from that of the moving vane), it is well to enclose the whole of the working parts as completely as possible in a metallic case or **screen** connected to the moving vane.

The simplest arrangement is that of Fig. 105, and consists of a fixed vane, A, and moving vane, N, the voltage to be measured being applied as shown at V. It is assumed, in this figure, that the instrument may be required for use with either pole at any potential above or below that of the earth, so that it is necessary to enclose the screen S within

[1] See also p. 235.

a case, C, which may be either of insulating material or of metal carefully insulated from both poles. In the latter event the case C should always be connected to earth, as shown at E.

A possible source of error in electrostatic voltmeters is an electric charge set up when cleaning the glass, but with careful design it is easy so to arrange the screen S that it completely surrounds the moving parts, and disturbance due to this cause is almost entirely eliminated, or, if necessary, the surface of the glass may be made conducting either by covering it with meshes of gold leaf or by coating it with a transparent conducting varnish (see p. 15).

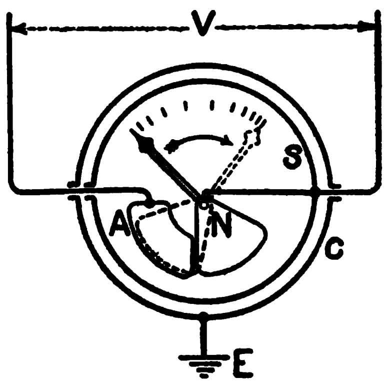


FIG. 105.—Shielded High Tension Electrostatic Voltmeter.

The practical design of electrostatic voltmeters falls usually into one of the following three groups, although no hard and fast line can be drawn :—

(1) Those for pressures of from 50 to 1,000 volts.

(2) Those for pressures of from 1,000 to 8,000 volts.

(3) Those for pressures of from 8,000 volts and upwards.

In the first class (**up to 1,000 volts**) a large number of fixed and moving vanes may be employed on a common axis giving the **multicellular arrangement, originally due to Kelvin.** This construction has been developed into a robust instrument suitable for switchboard work, one design on these lines, due to Hamilton, being illustrated in Fig. 106. The vanes are double-ended, and no pivots are employed, the movement being suspended by a fine wire, the torsion of which also gives the controlling force. Damping is provided for by means of a small paddle, attached to the lower end of the spindle and dipping into a pot of oil.

Another interesting instrument, suitable for this range of voltage, is that due to **Ayrton and Mather.** In this case the surfaces of the vanes take the form of parts of coaxial cylinders, and it is claimed that this construction enables the working clearance to be much reduced, so that the torque is considerable. Pivots and springs are employed in the usual way. The margin of safe excess of pressure is, however, no greater than in the multicellular pattern, and fuses are incorporated in the instrument terminals so as to protect the circuit from damage due to a fault in the voltmeter.

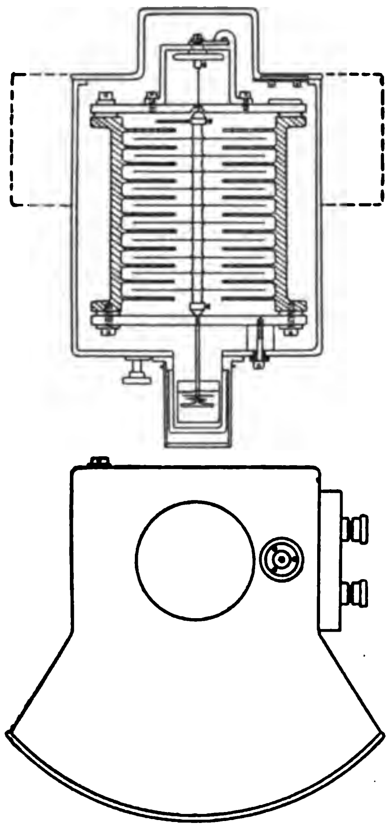


FIG. 106.—Shielded Multicellular Electrostatic Voltmeter.

With the instruments which fall in class 2 (**1,000 to 8,000 volts**) it is possible to use pivots and still have a liberal working clearance between the vanes. The weight of the moving parts, however, is such that ordinary pivots and jewels are not so good as the arrangement of two sharp steel points resting in polished steel cups or "V's," as shown in Fig. 14 (p. 35). Some arresting device must be provided to lift the points during transit.

An early example of this class is the Kelvin "butterfly" pattern voltmeter, which has been largely used for testing purposes. This instrument has vanes above and below a

horizontal axis which is supported on knife edges resting in V hooks. There are usually three ranges provided, the change from one to another being carried out by hanging small weights from a hook at the lower end of the moving system.

Fig. 107 shows another instrument of recent design, intended for switchboard use up to 8,000 volts. This affords a good illustration of screening (see p. 186). It has two fixed vanes and a moving needle. The latter is electrically connected to the pointer and dial. Carried upon the same insulator, is a metallic screen, which is con-

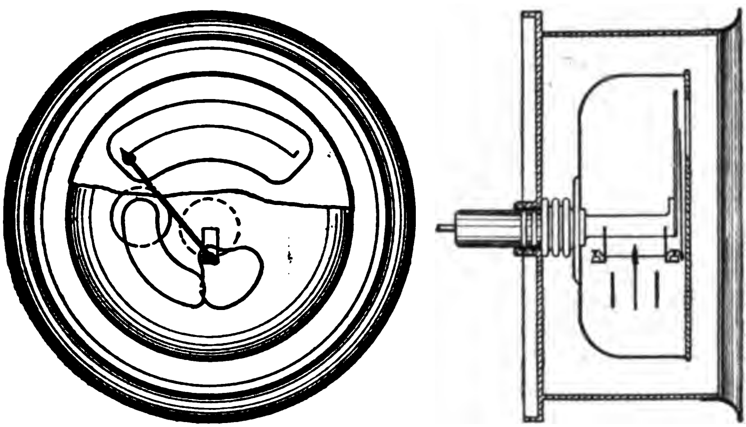


FIG. 107.—Shielded High Tension Electrostatic Voltmeter.

tinuous, except for an opening in the front through which the scale and pointer can be viewed. The fixed vanes are mounted upon another insulator by means of a stem passing through a clearance hole in the screen. The outer case is of metal, and can be connected directly to earth. As the whole movement is surrounded by the screen, it is entirely protected from external influences, and the readings are the same whether both poles are insulated or one of them is earthed. At the same time, the case, being earthed, affords absolute protection from danger of shock.[1]

[1] Dust on insulators is a common source of leakage, and may result in a serious shock if the case should happen to be insulated from earth.

Instruments employing the system of vanes shown in Figs. 105 and 107 are not suitable for working at pressures **above 8,000 volts** (alternating), since a brush discharge is liable to occur from the edges of the moving vane, even if rounded off and separated from the fixed vanes by a wide gap. In such cases, therefore, it is advisable either to adopt some means of extending the range without applying the whole pressure to the vanes or to adopt an entirely different design.

Peukert[1] showed that the range of an electrostatic voltmeter could conveniently be extended by connecting one or

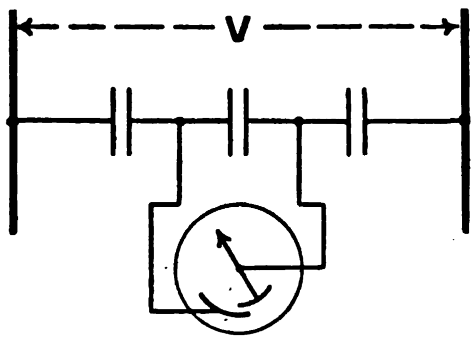


FIG. 108.—Extension of Range of Electrostatic Voltmeter by means of Condensers.

more **condensers** in series with it. In another arrangement a number of condensers are connected in series with each other across the pressure to be measured (V), and the voltmeter itself is joined across one of the series, as shown in Fig. 108.

The use of condensers is convenient for switchboard work, but the utmost care must be taken to guard against even a minute leakage across the instrument or the condensers. If this point is not attended to, the readings are liable to be greatly affected by change of frequency and, as it is impossible entirely to eliminate leakage, electrostatic voltmeters whose range has been extended by the use of

[1] *Electrotechnische Zeitschrift*, Vol. 19, p. 50.

condensers are not applicable to varying frequencies, nor, of course, can they be used on continuous current systems. A further matter of importance is the effect of the capacity of the leads employed to join the condenser to the instrument. It must be remembered also that all parts of the apparatus possess a capacity to earth which may produce a different effect on the potential between the vanes according to the relative potential between either pole and earth. These considerations have led to the following methods of working :—

(*a*) **Instruments so connected that one pole is earthed** (*e.g.* leakage detectors). One condenser should be used, connected on the "live" side of the instrument. The con-

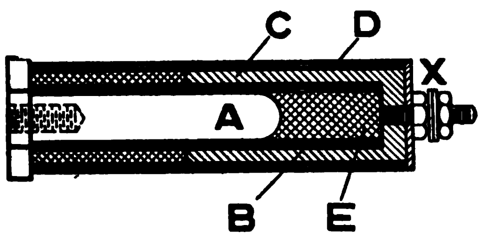


FIG. 109.—Condenser for Back Stem of Electrostatic Voltmeter.

necting lead should be short, not very thick, and should not be altered after calibration. A good arrangement is to screw the condenser on to one of the back connections of the instrument. A satisfactory form of condenser for this purpose is shown in section in Fig. 109. This consists of a cylindrical brass rod, A, screwed to the instrument terminal and surrounded by the metal tube C, to which the supply lead is attached at X. The two are separated by a tube, B, of micanite. Outside the tube C is another insulating tube, D, which prevents any appreciable surface leakage from X to A. The intervening space E is filled with insulating compound.

(*b*) **Instruments in which neither pole can be earthed,** or in which, for any other reason, the earth potential relation is not definitely prescribed. In this case three condensers can be employed, connected in series across the

pressure to be measured, as shown in Fig. 108, the instrument being joined across the centre one. The capacity of each of these condensers should be large compared with that of the instrument and that of either pole of the instrument to earth. The capacity of the connecting leads should also be reduced to a minimum. An investigation of this arrangement with reference to the shunting effect of the capacity of each pole to earth will show that the readings of an instrument so connected cannot theoretically be quite independent of changes in the earth potential relation. If, however, the capacity current of the series of condensers is about twenty times that of the instrument, and reasonable care is taken to avoid a large capacity from either pole to earth, the readings will not be adversely affected by varying the relative potential between any particular part of the apparatus and earth. Moreover, the readings are somewhat less affected by leakage currents due to dirt or moisture than with the simple series condenser. This is owing to the fact that the capacity current through the condensers is much greater compared with the leakage current, on account of the larger capacity employed. Also, equal leakage across all the condensers is without effect.

For the greatest accuracy and complete independence of frequency, however, it is advisable to employ an instrument in which the **potential is applied directly to the vanes,** without the intervention of condensers. The arrangement of vanes shown in Fig. 105 may be employed for ranges up to about 40,000 volts if the whole movement is immersed in oil, but the use of oil is not to be recommended on account of floating charges as well as of variations in dielectric constant.

E. A. Watson [1] has shown that by filling the instrument with highly compressed air a voltmeter of this form becomes available for almost any range, since air when compressed is a much better insulator than at atmospheric pressure.

For working in the usual way, however, and without oil immersion, the simple quadrant electrometer type has to be

[1] *Journal Inst. E.E.*, Vol. 43, p. 113 (1909).

abandoned for pressures exceeding about 8,000 volts, and a system on the lines of the attracted disc electrometer substituted. Amongst other advantages, this construction enables all edges to be well rounded on both fixed and moving elements, so that brush discharges are avoided. The earliest instrument of this type, that due to Kelvin, was constructed for pressures up to 100,000 volts. The movable vane was suspended, and was somewhat in the form of a flat scale pan, the fixed vane being placed about a foot below it. Owing to the small movement available, the connection between the movable vane and the pointer embodied a multiplying arrangement, a feature common to all voltmeters of the attracted disc type.

One maker employs two parallel oblong plates, the one fixed and the other hinged at the top. The control is gravity, and the movement of the hinged plate is magnified by a link arrangement connected to the pointer. This instrument is made for direct connection to the circuit up to 13,000 volts, and is fitted in an 8-in. round case of insulating material. For switchboard use, however, condensers are preferable above 10,000 volts.

Fig. 110 shows a more recent instrument of the attracted disc type, suitable for pressures up to 200,000 volts—that of **Abraham**—in which the planes of the working discs are vertical. The movable parts are suspended by the ligaments L, L, the controlling force being gravity. Interesting points in this design are the efficient air-damping dashpot A and the arrangement for varying the range. Each instrument is provided with four ranges, any of which may conveniently be brought into action by adjusting the distance between the fixed and moving vanes. The iron bedplate B is provided with accurately machined slides, and the fixed vane is capable of being clamped in any desired position. A scale of ranges is engraved on the bedplate, and a corresponding indicator is provided on the foot K of the fixed vane.

The moving plate D, which is attracted by F, is surrounded by a shielding disc or guard ring, E, which screens it from outside electrostatic influences. The movement of D is

conveyed to the pointer P by means of the rigid arm G, which carries a cord passing round the pulley O. The control being partly due to gravity, levelling screws (H) are provided.

The accuracy of this instrument is independent of the

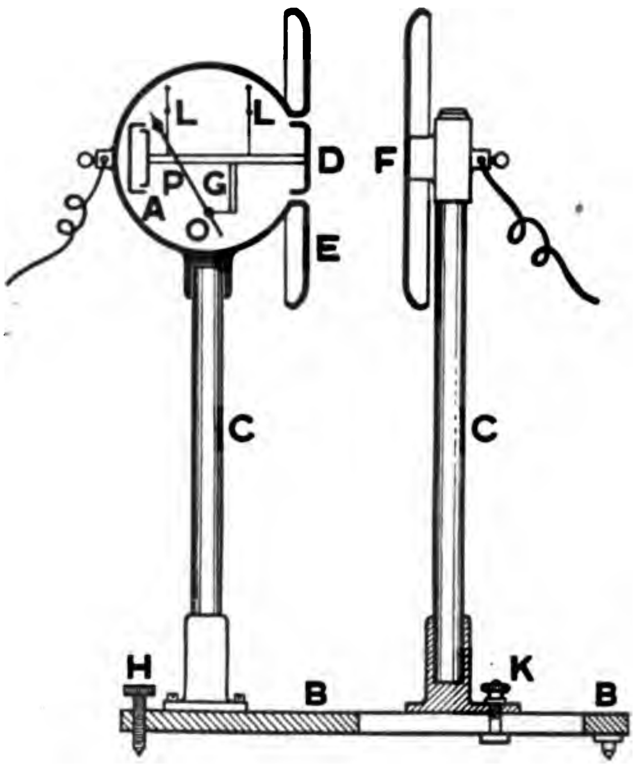


FIG. 110.—Abraham Electrostatic Voltmeter.

nature of the supply, whether continuous or alternating, and also of variations of frequency and wave form. The potential existing between either pole and earth, as well as stray electrostatic fields, are without disturbing effect upon the readings.

Another interesting design, also suitable for pressures up

to 200,000 volts, which employs oil and an attracted disc, is that due to **Jona**. This instrument is shown in section in Fig. 111. The pressure to be measured is applied to the terminals A and B, of which the latter is in metallic contact, through the supporting chain K, with the suspended plate C. The terminal A is joined to a sheet of tinfoil on the outside of the glass containing vessel D, and when electrified this plate induces a charge on another sheet of tinfoil, E, on the inner side of the glass. The plate C is therefore attracted by E, and causes the pointer to move across the scale F.

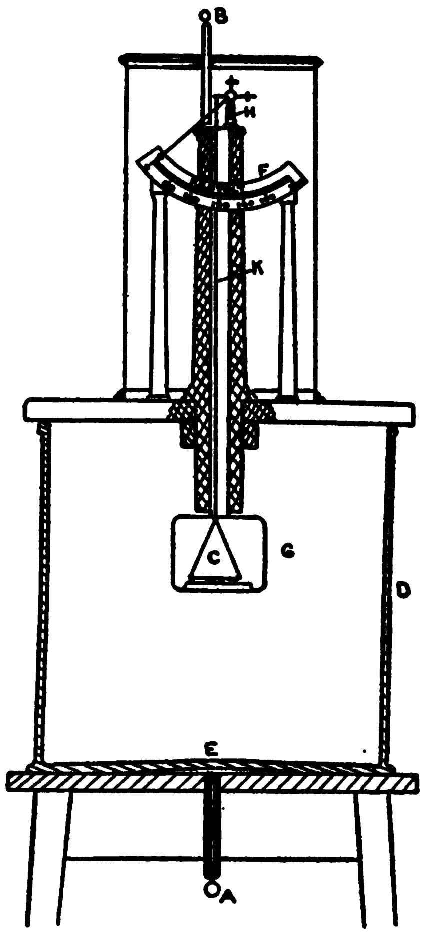


Fig. 111.—Jona Electrostatic Voltmeter.

The shield G, which is in metallic contact with C, and therefore at the same potential, serves to screen the instrument from external influences. The vessel D is nearly filled with insulating oil, which both damps the oscillations and increases the dielectric strength. Since the force of attraction depends on the specific inductive capacity of the oil, the instrument is calibrated with that which is subsequently to be used. The controlling weight H is adjustable, and two or more

weights are usually provided, to give different ranges. The scale is fairly evenly divided throughout the working range.

As mentioned on p. 184, it is necessary to bring the fixed and moving vanes of an electrostatic voltmeter as close to one another as possible, in order to obtain reasonable operating forces, but this also tends towards a low margin of safety, and since, particularly on high voltage circuits, considerable **overpressure surges** are liable to occur, some **protective device** becomes desirable, to prevent both damage to the instrument itself and short circuits on the system.

The devices most commonly used are—

(*a*) A spark-gap in parallel with the instrument.

(*b*) A fuse and high resistance in series with the instrument.

(*c*) A condenser in series with the instrument.

The spark-gap method must now be regarded as obsolete, unless used in conjunction with a series resistance. A serious defect is that, although the instrument may be protected, the risk of breakdown to the system is enhanced, as the spark-gap must be set to act at a lower voltage than the instrument, and when the gap sparks across, the supply current will, inevitably, follow.

Fuses form an adequate safeguard both to the instrument and to the system, but it is difficult to design one which will blow at a sufficiently small current to break the discharge without being itself destroyed. To meet these difficulties, a high resistance is connected in series with the fuse, and the current thus limited to a safe quantity. These resistances usually take the form of rods composed of a mixture of carbon with some non-conducting material, and may have a resistance ranging from 10,000 ohms to as much as 50 megohms. The capacity current flowing into the voltmeter is so small that the value of the resistance is without effect upon the reading of the instrument.

An ingenious combination of fuse and resistance is the Ferranti water fuse, shown in Fig. 112. This consists of a glass tube, B, full of water, mounted vertically and pro-

vided with a small hole at the upper end, A. The resistance of the column is adjusted to a suitable value by varying the degree of impurity of the water. If the voltmeter should break down, the current boils off the water in the tube and isolates the instrument. This device also serves to isolate the voltmeter should it be desired to do so, since it is mounted in a porcelain handle, E, and is provided with plugs and sockets, C C.

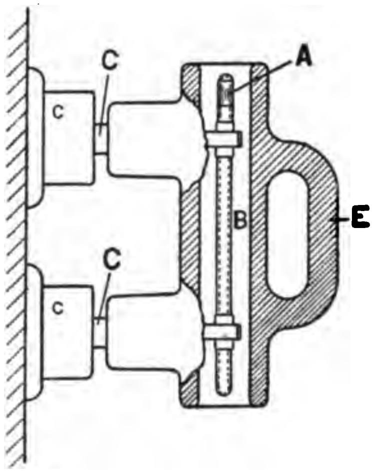


Fig. 112.—Ferranti Water Fuse for Electrostatic Voltmeter.

The use of **condensers** for extending the ranges of electrostatic voltmeters has already been dealt with on p. 190, and it need only be pointed out, in addition, that a well-designed condenser will not break down unless subjected to three or four times its normal working pressure, and thus constitutes an excellent safeguard both for the instrument and the circuit. The limitations to the uses of condensers, already alluded to, must be remembered, however, and they cannot be used indiscriminately, merely on account of their protective value.

Power Measurement.

The instantaneous power, or rate of dissipation of energy in any part of a circuit, is measured by the product of the instantaneous pressure across that part, multiplied by the instantaneous current. If the former be e volts and the latter i amperes, then the power in watts is, at any instant—

$$p = e \times i.$$

Since for **continuous current circuits** the instantaneous is the same as the steady value, the power also is steady, and

is determined by measuring volts and amperes and multiplying their values. It will also be observed that the direction of flow of power is dependent on whether the direction of current in the circuit agrees with or is in opposition to the applied pressure. In the case of a reversal of current without a corresponding reversal of terminal pressure, such as occurs, for example, when a motor is caused to act as a generator, the power may be written—

$$e \times (-i) = -p.$$

In other words, power is being returned to the system, and is therefore negative, whereas previously it was being absorbed by the machine and was positive. A reversal of supply pressure polarity, if it involves also a reversal of current, does not represent a reversal of power, since in this case—

$$(-e) \times (-i) = +p.$$

From this we may deduce that, in **alternating current circuits** in which the directions of both current and pressure reverse many times per second, the direction of power at any instant depends only upon the relative directions of pressure and current. The average power in such a circuit will therefore be a maximum when the directions of pressure and current are in agreement or in opposition throughout the whole cycle. For any other condition the product of $e \times i$ changes sign during the cycle, and the average power is the difference between that taken from and that given to the circuit, as indicated by the positive and negative values of p. In this case the value of the average power will be—

$$P = E \times I \times \cos \varphi,$$

where E and I are the root-mean-square or virtual values of the pressure and current, respectively, and φ is the electrical angle of phase displacement between these quantities. It will be observed that when the current is in phase with the pressure (*i.e.*, $\varphi =$ zero) the value of P is the same as for continuous current, and is a maximum. For all other angles the average value of the power is less, becoming

zero when $\varphi = 90$ electrical degrees. Under these conditions power is supplied to the circuit during one half of each cycle, and an equal amount is returned by it during the other half-cycle. For values of φ greater than 90° the power is negative (*i.e.*, reversed), the portion of the circuit under consideration becoming a generator and supplying power to the remainder.

It is possible, therefore, **to measure alternating power by means of a voltmeter, ammeter, and phase meter,** and where there is considerable displacement between the pressure and current this method has advantages. The usual method, however, is to employ a **wattmeter** —an instrument designed to indicate directly the average value of the power. Several forms are discussed from a constructional point of view on pp. 209 *et seq.*, but the fundamental electrical condition in them all is that the force exerted on the moving system, at any instant, shall be directly proportional to the product of the corresponding instantaneous values of pressure and current. If, as is usual, the instrument is required to indicate the average value of the power in an alternating current circuit, the moving system must have a natural time of oscillation very considerably greater than that corresponding to one cycle.

The **essential elements of a wattmeter** are therefore—

(1) A current circuit.

(2) A pressure circuit.

(3) A mechanism for indicating the instantaneous product of current and pressure and averaging the result over short intervals of time.

A brief description of the simplest form of wattmeter, the so-called "dynamometer" pattern (see p. 209), will make the matter clearer. In this a pivoted or suspended coil, usually wound with very fine wire, moves in the magnetic field due to a fixed coil carrying the main current. The fine wire moving coil is connected in series with a high non-inductive resistance across the mains, the connections being as shown in Fig. 113, in which CC represents the current coil, VC the volt coil, and R a non-inductive resistance in series with the latter. This resistance is made as large

as possible, since the current flowing through it causes a continual waste of power. It should also be made of a material with a negligible temperature coefficient, in order that the readings may be unaffected by temperature.

If i_1 represents the instantaneous current in the current coil and i_2 the instantaneous current in the pressure coil, and if there is no iron and no disturbing magnetic field due to currents in neighbouring conductors, we have—

$$\text{Torque} = a\, i_1 \times i_2,$$

but i_2 is proportional to e, and therefore we have—

$$\text{Instantaneous torque} = a\, i_1 \times e.$$

Owing to its inertia, the moving system is unable to

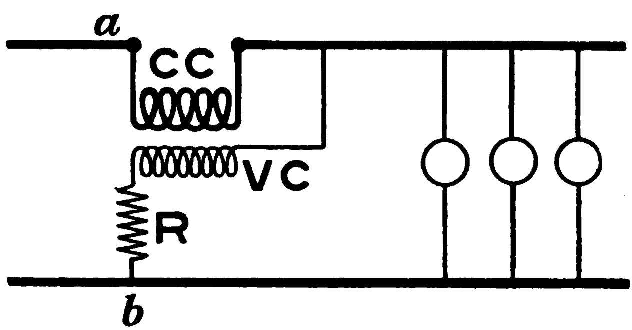


FIG. 113.—Simple Dynamometer Wattmeter Connections.

follow the alternations, and the reading therefore corresponds to the time average of the power.

It should be observed that the pressure winding may be connected to the main circuit on either the generator or load side of the current coil CC. In the former case, the power absorbed by the current coil is included in the measurement, and in the latter, that absorbed by the pressure circuit. When the error on account of either of these losses is negligible the pressure coil is usually connected on the generator side, that is between a and b, Fig. 113, but when it is desirable that allowance should be made for instrument losses, it is preferable to connect the pressure circuit on the

load side of the current coil, as shown in Fig. 113, since the pressure circuit loss, being constant under steady voltage conditions, can generally be calculated once for all.

Dynamometer wattmeters may readily be **compensated for the loss in the pressure circuit,** as indicated in Fig. 114, by including with the main current winding one of fine wire, following the former throughout its length. This auxiliary winding, AW, is connected in series with the pressure coil PC in such a way that its magnetic effect is in opposition to that of the pressure current in the main coil CC. It thus

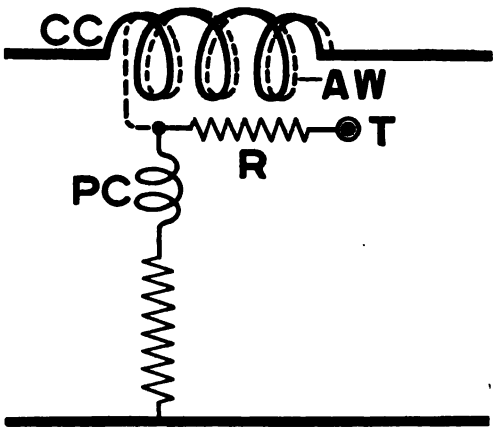


FIG. 114.—Compensation for Pressure Circuit Losses in Wattmeter.

cancels the magnetic effect of the pressure current flowing through the main coil, under all conditions, and the instrument indicates only the power absorbed by the load. An additional terminal may be added, as shown at T, which enables the auxiliary winding to be cut out when not required and a resistance, R, equal to that of the winding AW substituted for it.

Polyphase Power Measurement.

Fundamentally, the methods of using wattmeters on a polyphase circuit involve subdividing it into a number of

single phase sections and employing a separate wattmeter in each of them. It is often possible, however, to group the wattmeters in such a way as to reduce the number of instruments without sacrificing accuracy. Moreover, a further advance may be made by causing the required number of single phase wattmeter elements to actuate a common pointer, so that their effects are added together, and the total power is obtained from a single reading.

For the purpose of polyphase power measurement it is necessary to consider, besides the number of phases, the number of "wires" or mains used to convey the current. The commonest cases, starting with the single phase system, are shown on p. 203.

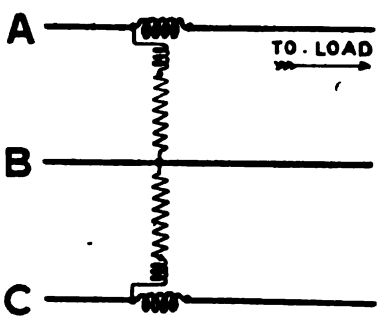


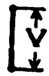
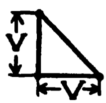
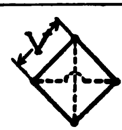
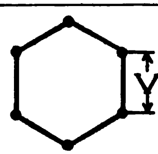
FIG. 115.—Power Measurement in Three-phase Three-wire System.

(*a*) **Single phase two-wire** has already been dealt with.

(*b*) **Single phase three-wire** involves two single phase wattmeters with one current coil in each outer, and the respective pressure circuits connected between the corresponding outer and the neutral line (see Fig. 115).

(*c*) The **two-phase four-wire** system is merely a duplication of single phase conditions, the phases being entirely separate. This case involves the use of either two single phase instruments or two single phase elements actuating a common pointer.

Systems (*d*) and (*e*) (**two-phase and three-phase, three-wire**) are in many respects similar to each other and to system (*b*). It is interesting to note that in any of these systems the power is transmitted by three wires and may be measured by means of two single phase wattmeters or an equivalent combined instrument. The essential condition for the measurement of polyphase power in any system fed

	System.	Vector Diagram.	No. of Wattmeter elements required.
(*a*)	Single phase two-wire		1
(*b*)	,, ,, three-wire		2
(*c*)	Two-phase four-wire [1]		2
(*d*)	,, ,, three-wire		2
(*e*)	Three-phase three-wire		2
(*f*)	,, ,, four-wire		3
(*g*)	Four-phase four-wire [1]		3
(*h*)	Six-phase six-wire		5

[1] There is usually no distinction made between these two systems.

by three lines is that the two current coils shall be connected one in each of any two of the lines, their respective pressure circuits being joined between these lines and the remaining one, as shown in Fig. 115. For the two-phase three-wire case the current coils are invariably connected in each of the outer lines, so that in Fig. 115 line B is the common one. This arrangement gives a symmetrical loading of the windings of the wattmeter, but the general principle of connections will give correct results no matter which two lines are chosen for the current coils, and is independent of the state

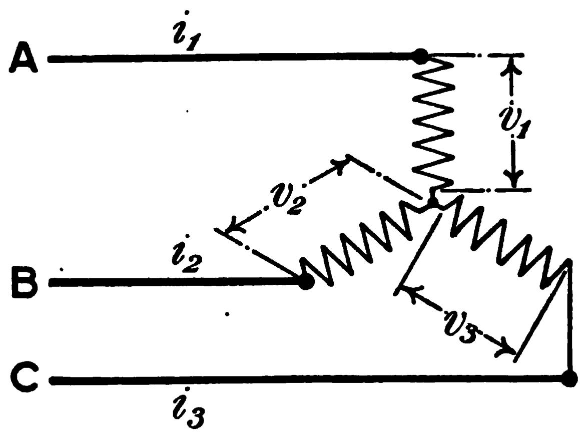


FIG. 116.—Three-phase Load.

of balance of the load with regard to either current, voltage, or phase angle.

Consider, for example, the system illustrated in Fig. 116, in which v_1, v_2, and v_3 are the pressures at a certain instant between each line and the neutral point, while i_1, i_2, and i_3 are the corresponding instantaneous line currents. It is assumed that currents flowing towards the neutral point are positive, as are also the pressures when the lines are positive with reference to it. The load is here assumed to be star-connected, but if delta-connected an equivalent star-connected load can always be found. By Kirchoff's law—

$$i_1 + i_2 + i_3 = 0$$
$$\text{or } i_2 = -(i_1 + i_3).$$

From first principles, the total instantaneous power is—

$$p = i_1 v_1 + i_2 v_2 + i_3 v_3,$$

or, substituting for i_2,—

$$p = i_1 v_1 - i_1 v_2 - i_3 v_2 + i_3 v_3$$
$$= i_1 (v_1 - v_2) + i_3 (v_3 - v_2).$$

But, for instantaneous values, $(v_1 - v_2)$ is the pressure between A and B, while $(v_3 - v_2)$ is the pressure between B and C, so that the whole expression represents the sum of the products of the instantaneous pressures and currents in the two wattmeter elements. The algebraic sum of the effects on the two elements will therefore be a measure of the instantaneous power, and, since this is true for any instant, the sum of the wattmeter readings will be a true average of the power flowing. The arrangement is therefore quite independent of the relative voltages, currents, and phase displacements in the three lines.

(*f*) On a **three-phase four-wire** system the measurement involves the use of three wattmeters of which the current coils are connected one in each of the phase lines or outers, and the pressure coils between the respective phases and the neutral line. The sum of the three readings then gives the true power under all conditions of load. The three moving coils may be attached to a common spindle and pointer, to avoid calculating the sum of three separate readings.

Systems (*g*) and (*h*) (**four-phase and six-phase**) are equivalent, respectively, to two-phase four-wire and three-phase six-wire, since unbalanced loading never occurs in ordinary practice. The usual course is, therefore, to treat them as two or three-phase circuits respectively. If it is required to provide for irregular loading, the number of wattmeters required will be one less than the number of wires employed.

Balanced Loads.—In many cases, such as the supply to

motors or rotary converters, it is possible to assume that the loads on the various phases are so nearly equal that it is only necessary, for commercial accuracy, to measure on one phase and to multiply the reading by the number of phases. A strictly "balanced" circuit is one in which the currents, pressures and phase angle between line current and pressure to neutral are the same for each phase, and under these conditions it is possible to employ the following arrangements[1] :—

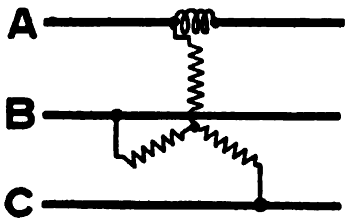


FIG. 117.—Three-phase Balanced Load Wattmeter.

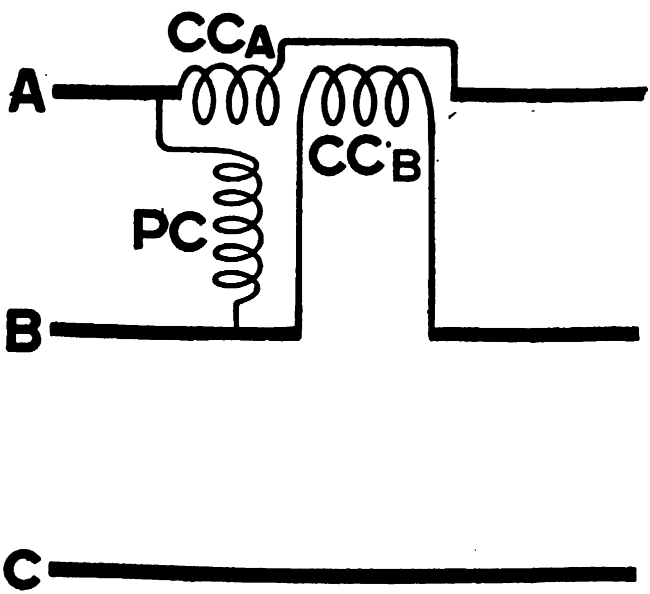


FIG. 118.—Three-phase Balanced Load Wattmeter.

[1] Truly balanced systems are rare, and unless first cost is a serious consideration, the use of methods depending for their accuracy upon exact balance is to be deprecated.

For **two-phase three-wire or four-wire circuits** a single phase wattmeter in one phase. In the three-wire case the current coil is preferably connected in one of the outers.

For **three-phase three-wire systems** a single wattmeter can be used with its current coil in one of the lines and its pressure circuit connected from this line to the neutral point, if it is available.[1] If it is not available, the wattmeter must be provided with a "star" resistance, as shown in Fig. 117. This consists of three equal resistances, one of which includes the pressure coil of the wattmeter.

In another arrangement the current coil is divided into

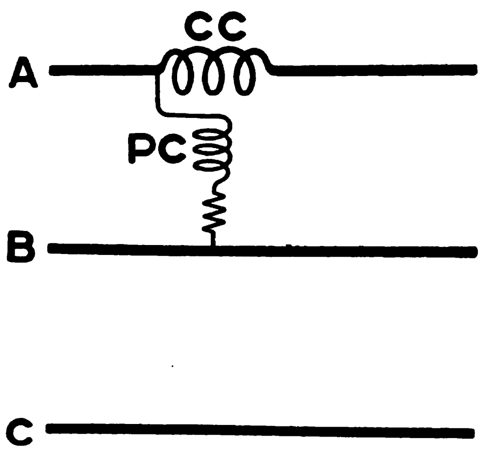


FIG. 119.—Three-phase Balanced Load Wattmeter.

two equal sections, CCA and CCB, one being reversed, and the resultant flux is then in phase with the pressure between lines A and B, Fig. 118. In Fig. 119 the connections are given of another arrangement for three-phase balanced loads, which is particularly suitable for use with wattmeters of the induction type.[2] In this case the current in the pressure circuit is given a lag or lead of 30°, the object in each case being to bring the current and pressure fluxes into phase. This is done, in the first arrangement (Fig. 118), by dividing the

[1] It is often possible to obtain the neutral point pressure although no current-carrying main is laid.

[2] See p. 225.

current coil, and in the second (Fig. 119) by introducing a lag or lead of 30°.[1]

Unbalanced Loads. — Where the different phases are likely to be unsymmetrically loaded it is usually necessary to employ the number of wattmeters specified in the table on p. 203. The number there given, however, allows for variations of pressure, current, and phase angle, whereas in practice the pressures may generally be assumed to be almost symmetrical. This permits of some simplification, such as, for example, in the case of a three-phase four-wire circuit, where it is possible to measure the power by two

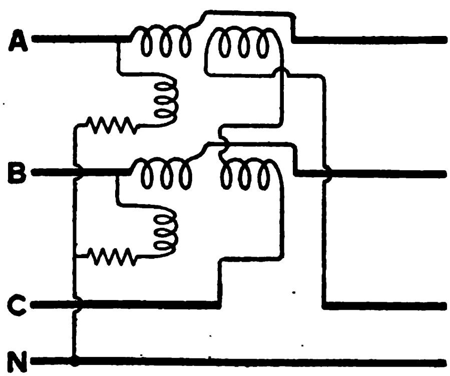


FIG. 120.—Three-phase Four-wire Wattmeter.

wattmeters each with split current coils and connected as shown in Fig. 120.

In all cases **pressure or current transformers** may be employed to avoid the direct connection of wattmeters to high pressure circuits. Transformers for use with wattmeters must be designed to give secondary pressures and currents which are not only accurately proportional to those of the primaries, but are also in phase with them (see p. 313). Further information with reference to the grouping of instrument transformers will be found on pp. 330 *et seq.*

[1] This method might be applied to any number of phases by modifying this angle, the object being to obtain the same phase relationships as though the pressure winding were connected between the line carrying the current coil and the neutral point of the system.

Wattmeters.

These instruments are usually constructed on one of the following principles :—

(*a*) Dynamometer.
(*b*) Induction.
(*c*) Electrostatic.
(*d*) Hot wire.

Of these, the first two are the only types of importance from the industrial standpoint.

Dynamometer wattmeters depend, as has been explained (p. 199), on the electro-magnetic interaction between fixed and moving coils. The force exerted on the moving system at each instant is proportional to the product of the currents in the fixed and moving coils, so that if the latter takes a current proportional to the instantaneous pressure the torque is proportional to the instantaneous product of current and pressure and therefore to the power.

The movement of the coil is usually controlled by a spring or pair of springs, the current also being led into and out of the coil either by this means or by fine silver ligaments (see p. 32). For instruments of the highest precision the spring usually takes the form of a cylindrical helix and is attached to a torsion head. When current is passing, the suspended coil deflects against a stop, but is restored to the zero position by turning the torsion head, so as to balance the deflecting torque against that due to the spring when twisted through a measured angle. The scales of such instruments are uniformly divided, since the fixed and moving coils always occupy the same relative positions (approximately at right angles, where the torque is a maximum), and the control due to the spring is proportional to the angle through which it is twisted (see, however, p. 28).

A good example of a wattmeter of this class is that of **Duddell,** the arrangement of the coils being shown in Fig. 121. It should be noted that with the suspended pressure coil VC, in the form of a figure 8, the arrangement becomes astatic and is therefore practically unaffected by stray fields.

The current coils CC are made up of ten strands of wire twisted together, each strand being insulated from the others. These are all brought out to a plug board, which enables any grouping of the sections in series or parallel to be made and thus provides for a wide range of current.

A wattmeter having astatic coils, similar to that just described, is due to **Drysdale.**[1] This instrument has two distinct dynamometer systems, similar to that of Fig. 121, mounted one above the other on a common spindle, and is therefore suitable for the measurement of three-phase unbalanced loads direct. To minimise interference between the two movements, they are fixed at right angles to one

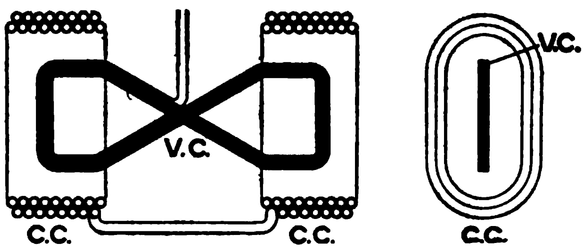


FIG. 121.—Duddell Wattmeter.

another. As in the Duddell wattmeter, the fixed coils consist of stranded conductors, which can be connected in series or parallel groups to extend the range. In this case a rotary switch is employed instead of plugs. The following groupings may be taken as typical :—

Number of coils in series . . .	10	5	2	1
" " parallel . .	1	2	5	10
Range in amperes per movement .	5	10	25	50

Above 250 amperes (25 amperes per coil) windings such as those of Fig. 121 become difficult to construct, and a horizontal form of moving coil has been developed which is

[1] C. V. Drysdale, *Electrician*, Vol. 76, pp. 523, 558, 593 (1916).

embraced by two flat fixed coils. The moving system is suspended by a silk thread and controlled by a spiral spring and large torsion head, in the usual manner.

An ingenious form of **tubular wattmeter** suitable for heavy currents is due to A. E. Moore.[1] Fig. 122 shows the current element. The current passes in by the central conductor A,

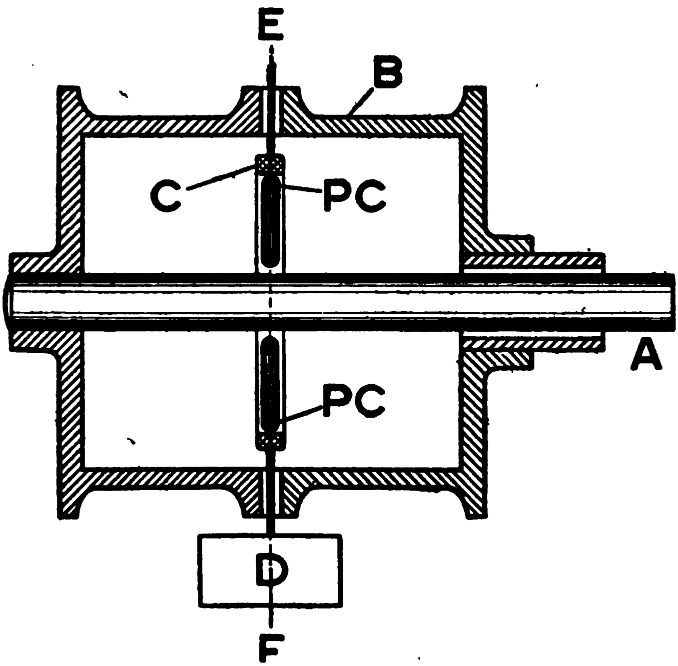


FIG. 122.—Concentric Wattmeter, Current Element.

which may be tubular, and back by the outer shell B to the other terminal. A magnetic field is produced, concentric with A, and in this swings the astatic moving coil, shown in Fig. 123 and consisting of two D-shaped coils, PC, bound to an ebonite ring, C. A damping vane, D, dips in an oil vessel (not shown). In order that the moving coil may be introduced into the current element, the latter is split along the

[1] A. E. Moore, *Journal Inst. E.E.*, Vol. 55, p. 380 (1917).

centre line EF (Fig. 122), the two parts being bolted firmly together. Such an arrangement allows of the heaviest currents being measured, and precludes all interference by stray magnetic fields, which is a most serious source of error in such instruments.

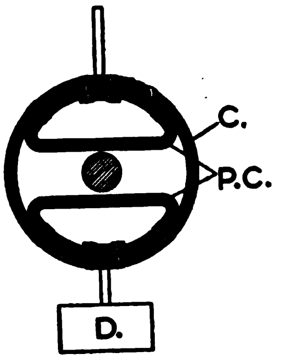


FIG. 123.—Concentric Wattmeter, Pressure Element.

For rapid working **deflectional wattmeters** provided with a pointer and scale are essential. Fig. 124 shows the working parts of a typical switchboard instrument, in which C, C, are coils forming the current element, while PC is the pivoted pressure coil. Other details shown in the figure are the flat helical control spring S and air-damping chamber N. The case is usually of cast iron, which is useful in screening the movement from the effects of stray magnetic fields.

The **scale** shown in Fig. 124 is taken from an actual instru-

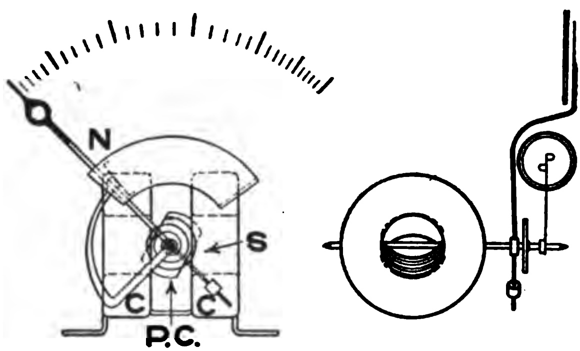


FIG. 124.—Working Parts of Deflectional Wattmeter.

ment, and is typical. Some ingenuity has been directed to obtaining uniformly divided scales with deflectional dynamometer wattmeters, and mention may be made, in this connection, of an early arrangement of Siemens and

Halske and of a design due to Heap. In the former instrument the main current flows through a fixed coil the upper and lower parts of which are bent into the form of a circle concentric with the axis of the moving coil. Thus the current flows across the instrument in two semicircular parallels, over the pivoted pressure coil, and returns in two similar parallels below it. This arrangement results in a practically uniform radial field, and hence a uniformly divided

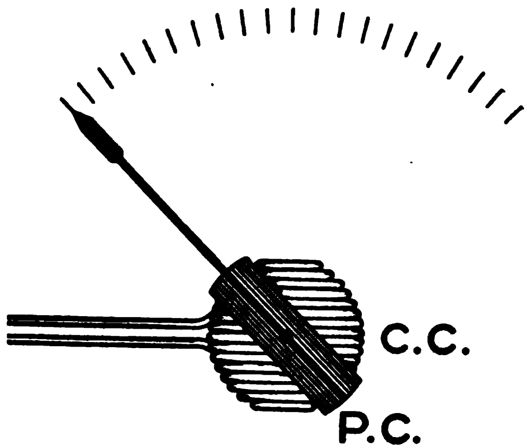


FIG. 125.—Heap's Wattmeter.

scale. It is inefficient, however, as regards control, and has been abandoned.

In **Heap's** arrangement the current coil is wound in the form of a small sphere, CC, and the pressure coil PC swings outside it (Fig. 125). This arrangement produces an approximately radial field and therefore a uniform scale, but has the disadvantage that both the self-induction and weight of the moving coil are considerably increased. A reasonably uniform scale is, however, easily obtained with the simple arrangement of coils shown in Fig. 124, while the ratio of operating force to weight of moving parts (see p. 36) is considerably better than with either of the foregoing arrangements.

The principal **sources of error** requiring attention in dynamometer wattmeters when used on alternating current circuits are—

(*a*) The self-induction and capacity of the pressure circuit.

(*b*) Eddy currents in any metal employed in the construction close to the moving coil.

(*c*) "Transformer effect"—mutual induction between series and pressure coils (see p. 178).

(*d*) Earth's field effects (see p. 12).

(*e*) Change in distribution of current in series coil, causing a change of torque with frequency (skin effect).

It has been shown that in a true wattmeter the reading is a measure of the time average of the product of the instantaneous pressures and currents, this being equal to $I \times E \times \cos\varphi$ for alternating currents of sinusoidal wave form. In a dynamometer instrument the reading depends upon the time average of the product of the currents in the pressure and current coils, and it is essential therefore that the current in the pressure circuit should be strictly proportional to, and in phase with, the pressure at its terminals. In other words, the pressure circuit must be free from **inductance** and capacity. It is, of course, impossible to fulfil this condition absolutely, since the moving coil itself must possess inductance, but it is easy for the winding to form such a small part of the pressure circuit that the effect of its inductance is "swamped" by the total ohmic resistance and becomes negligible.

Assuming that the inductance of the pressure circuit causes the current to lag behind the applied pressure by a small angle, α, the instrument reading will be proportional to—

$$I\,(E\cos\alpha)\cos(\varphi \pm \alpha),$$

since the current in the pressure circuit is reduced in magnitude in proportion to $\cos\alpha$, and the actual angle between the

currents in the fixed and moving coils is $\varphi \pm \alpha$. Now, since α is small, $\cos \alpha = 1$ (nearly), and hence—

$$\text{True watts} = \text{reading} \times \frac{\cos \varphi}{\cos (\varphi \pm \alpha)},$$

the error introduced, expressed as a percentage of the watts, is—

$$\left\{1 - \frac{\cos (\varphi \pm \alpha)}{\cos \varphi}\right\} \times 100$$
$$= \left\{\frac{\cos \varphi - \cos \varphi \cos \alpha \pm \sin \varphi \tan \alpha}{\cos \varphi}\right\} 100,$$

or, taking $\cos \alpha = 1$, the percentage error is approximately $\pm\ 100 \sin \alpha \tan \varphi$, or, neglecting the difference between α and its sine, the percentage error is $\pm\ 100\, \alpha \tan \varphi$.

Sometimes, it is more useful to know the error as a percentage of the volt amperes $\left(i.e., \text{ of } \dfrac{\text{watts}}{\cos \varphi}\right)$. In this case the error amounts to $\pm\ 100 \sin \alpha \sin \varphi$ (or approximately $\pm\ 100\, \alpha \sin \varphi$) per cent. of the volt amperes.

If φ is a lagging angle, the effect of inductance in the pressure circuit is to increase the wattmeter reading, so that the difference between φ and α must be used, but for leading currents the wattmeter reads low, and the sum of φ and α has to be taken. Since $\cos \varphi$ is zero when $\varphi = 90°$, it follows that the greatest percentage errors are introduced when working at low power factors. Drysdale has shown[1] however, that a more rational convention is possible.

True watts, $W = I \,.\, E \cos \varphi$.

Wattmeter reading, $W^1 = I \,.\, E \cos \alpha \,.\, \cos (\varphi - \alpha)$.

Hence—

$$\text{Correction} = W^1 - W = IE\,\{\cos \alpha \cos (\varphi - \alpha) - \cos \varphi\}$$
$$= IE \sin \alpha \sin (\varphi - \alpha).$$

This correction may be reduced to terms of the time constant L/R of the pressure circuit as follows :—

[1] *Electrician*, March 15th, 1901, and Jan. 14th, 1916.

Since α is extremely small, $\sin\,\varphi$ may be written for $\sin\,(\varphi - \alpha)$, and $\sin\,\alpha = \tan\,\alpha = \frac{L\,w}{R}$, where $w = 2\,\pi \times$ frequency. Hence—

$$\text{Correction} = W' - W = \frac{L\,w}{R}\,.\,EI\,\sin\,\varphi.$$

The correction is seen not to be a multiplier, as in the previous case, but an amount added to or subtracted from the reading of the instrument. The previous correction becomes indeterminate when φ approaches 90°, whereas the latter does not, and is easily applied in all cases. The maximum possible error due to inductance in the pressure circuit is thus $\frac{L\,w}{R}\,.\,E\,I$. Or, reduced to scale divisions, if EI at unity power factor carries the pointer to the top of the scale the expression $\frac{L\,w}{R}$ represents the maximum possible inductance error, expressed as a fraction of the scale length.

In a given wattmeter the angle α increases with the frequency, so that for instruments which are intended to operate on variable or very high frequencies it is essential that the inductance of the pressure circuit should be reduced to the lowest value possible.

It is rather difficult to determine the inductance of the pressure circuit, but in a good modern instrument the error introduced is usually negligible and should not exceed say one half-scale division, even for power factors as low as 0·1.

The effect of the **capacity** of the pressure circuit is also negligible for modern instruments working on pressures up to 1,000 volts. To avoid errors on this account, the resistance is usually subdivided into a number of sections each wound on a separate flat card of insulating material (see also p. 53), the capacity between the first and last of n sections being $\frac{1}{n}$ of that between adjacent sections. For testing instruments intended to be connected direct to high pressure

circuits, however, the capacity in parallel with the pressure circuit resistance may become of some importance.

In Fig. 126 the distribution of capacity is indicated by a number of condensers in two groups, representing the capacity between adjacent sections and to earth, respectively. The former (on the left) has the effect of increasing the current in the moving coil and causing a lead; the latter (on the right) will have the opposite effect, it being assumed that the instrument coil is earthed as shown (this being a common

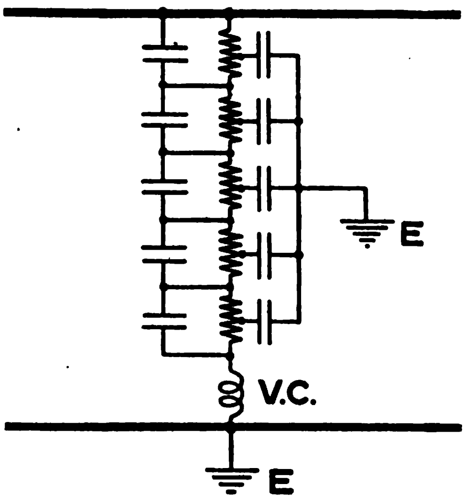


FIG. 126.—Effect of Capacity in the Pressure Circuit of a Wattmeter.

practice when using wattmeters on high pressure circuits). To minimise the capacity between the resistance sections and earth, the whole of the resistance frame and case should be constructed, as far as possible, of insulating material and ample clearances allowed at all points. If these precautions are observed, the effect of capacity may be neglected for all pressures.

The effects of **eddy currents** in the metal parts of a wattmeter or its case are sometimes a serious source of error, particularly at high frequencies and low power factors. Suppose, for example, that the wall of a metal case is close

behind the current coil. The field due to the latter will induce an E.M.F. in the metal lagging 90° behind the flux, that is to say, lagging practically 90° behind the main current. The eddy current circuit being fairly non-inductive, these currents will be nearly in phase with the E.M.F. producing them, and will therefore lag by practically 90° behind the main current. When used on a non-inductive load such a wattmeter will show no appreciable error, since the current in the pressure circuit is then in phase with the main current, and consequently nearly 90° out of phase with the eddy currents. On an inductive load, however, the smaller the power factor the more nearly will the current in the pressure circuit agree in phase with the flux due to the eddy currents, and consequently the greater will be the error.

The effect of such eddy currents is, fortunately, opposed to that due to self-induction in the pressure circuit, so that to a certain extent these two sources of error neutralise each other. Again, the resultant flux due to the current in the fixed coils, combined with that due to eddy currents, lags behind the main current, so that if this lag is by accident or design equal to that of the current in the pressure circuit behind the applied pressure, the correct electrical angle will exist between the current in the pressure coil and the series flux in which it is working.[1]

If the moving coil were wound on a metal former, the eddy currents induced in it would cause a considerable torque, and for this reason the moving coil is invariably so constructed as to avoid the use of metal except for the winding.

Owing to the fact that the field due to the current coil is, as a rule, many times greater than that due to the pressure winding, it follows that in certain positions of the latter a considerable E.M.F. may be induced in it. This "**transformer effect**" due to mutual induction is often regarded as a source of error, but a little consideration will show that, since the E.M.F. so produced is 90° out of phase with the

[1] See paper by Edgcumbe and Punga, *Journal Inst. E.E.*, Vol. 33, p. 167 (1904), also Dr. C. V. Drysdale's contribution to discussion on same.

main flux, the current induced in the volt coil will also be 90° out of phase with the main current (since the pressure circuit may be assumed to be non-inductive), so that no torque is produced. In any case the induced E.M.F. is not large, and the effect is seldom appreciable. The zero type of dynamometer in which the coils are always at right angles to one another is inherently free from mutual induction errors.

Drysdale was probably the first seriously to attempt to increase the working forces in dynamometer instruments by the use of a **magnetic circuit containing iron**. The Drysdale iron-cored wattmeter consisted of a laminated electro-magnet the winding of which carried the main current, while the pressure coil swung in an annular gap, much as in the case of a moving coil permanent magnet instrument. It was found in practice, however, with this construction that either the lag due to hysteresis was excessive, or else the air-gap had to be opened out to such an extent that the increased sensitivity due to the use of iron was almost *nil*. As a result, although Drysdale undoubtedly pointed out the fundamental principle that the air-gap reluctance should be large compared with that of the iron, the particular form adopted by him did not come into extensive use.

In the case of an ironless dynamometer wattmeter the most important consideration is, as has been seen, the elimination of self-inductance in the pressure circuit (p. 214). With an iron-cored instrument two other considerations have to be taken into account. For use with continuous current the hysteresis in the iron introduces the well-known hysteresis error, and when used with alternating current hysteresis and eddy currents in the iron cause a phase error. As regards the first, it was shown on p. 58 that if the ampere turns required to send the flux through the iron were $\frac{1}{n}$ of those required for the air-gap, the effective hysteresis was reduced to $\frac{1}{n}$ of that in the iron.

The **effect of iron losses** (hysteresis and eddy currents) is discussed at length when dealing with instrument transformers (pp. 316 and 319), and it will suffice here to point out that they cause a phase displacement between the

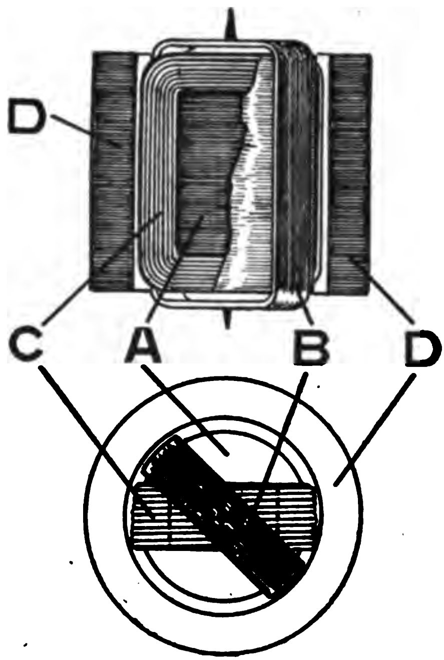


FIG. 127.—Murphy Ironclad Wattmeter.

current and the magnetic flux. It can be shown (see Fig. 190) that approximately—

$$\tan a = \frac{\text{iron loss in watts}}{\text{volt amperes in current coil,}}$$

where a is the phase displacement between current and flux.

These considerations show that it is of vital importance to minimise eddy currents and to make the reluctance of the iron small compared with that of the air-gap, and this entails a well-laminated iron path of minimum length and of maximum area.

Such an instrument (due to **L. Murphy**) is shown in Fig. 127. The current coil C is carried in a slot in the core A on the lines of an H armature, and the moving coil B swings in the air-gap formed between the core A and the yoke D. It is easy, with such a construction, to make the effects of hysteresis and eddy currents quite negligible and at the same time to secure large working forces and freedom from errors due to stray fields.

Sumpner has attacked the problem in a somewhat different manner. His wattmeter, which is considerably more complicated than that just described, is illustrated

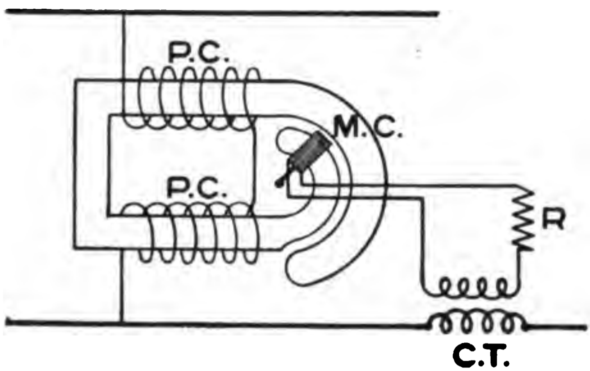


FIG. 128.—Sumpner Wattmeter.

diagrammatically in Fig. 128. PC represents the winding of an electro-magnet connected across the mains, and MC the moving coil. This coil is connected through a high resistance, R, to a current transformer CT, of the air-cored type. In this transformer, called by Sumpner a "quadrature transformer," the secondary E.M.F. is 90° out of phase with the primary current. The secondary circuit being almost non-inductive, the current flowing through the moving coil will be in phase with this E.M.F., and will therefore be 90° out of phase with the primary current. The pressure coil PC is made as inductive as possible, so that its flux lags nearly 90° behind the impressed voltage, and consequently for loads of unity power factor the current in the moving

coil will be in phase with the flux due to the pressure coil, so that the instrument is a true wattmeter.

It should be observed that the degree of saturation of the magnet iron is comparatively unimportant for shunt excitation, since the flux will be nearly proportional to the applied voltage.[1] On account of the inefficiency of the current transformer, this instrument is not appreciably better than the ordinary air-cored dynamometer pattern in its ratio of operating torque to weight for a given power consumption. The difficulty of obtaining precise quadrature on both pressure and current circuits is, moreover, considerable, and there is liability to interference with the quadrature transformer by stray fields. To minimise this effect, the transformer is usually built within a laminated iron shell. These difficulties increase at low frequencies, and in any case the instrument cannot be used at frequencies differing widely from that at which it has been calibrated.

Astatic Dynamometer Wattmeters.—For the purpose of rendering an ordinary dynamometer wattmeter independent of stray fields, two complete dynamometers may be mounted one above the other with a common spindle. If connected in this way, with the magnetic field passing in opposite directions through the upper and lower elements, the arrangement is astatic.

Polyphase Dynamometer Wattmeters.—A similar movement is suitable for polyphase wattmeters, each single phase element being connected to the circuit in accordance with the particular scheme of connections required for the measurement in view as described on pp. 201 to 205.

For work of this kind the condition for accurate operation is that the two elements shall be electro-magnetically independent of one another, *i.e.*, the field due to the current coil of one element shall not stray through the pivoted coil of the other element, or it would produce a torque. This condition is satisfied in non-deflectional wattmeters by placing the two elements at right angles to one another, as illustrated in Fig. 129. It will be observed that the magnetic axis

[1] See also p. 171.

of each pressure coil is in line with any stray field due to the other current coil, so that no deflectional torque is produced. This arrangement does not entirely meet the requirements of a deflectional instrument, however, and the

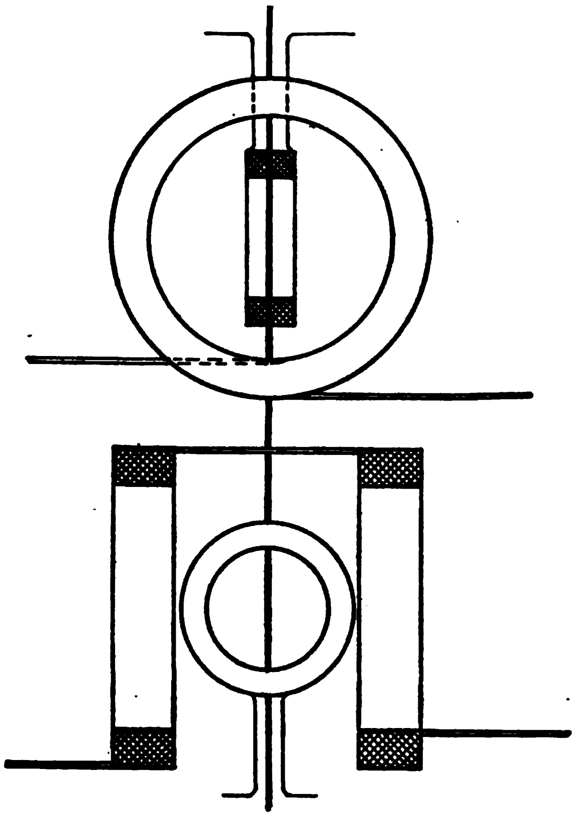


FIG. 129.—Polyphase Dynamometer Wattmeter.

best safeguard is to keep the two elements a reasonable distance apart.

Other points of importance in the construction of polyphase wattmeters are that the sensitiveness of all elements shall be the same and shall follow the same scale. If these points are not carefully attended to, the instrument will

read incorrectly on unbalanced loads and at low power factors.

Continuous Current Wattmeters.

The dynamometer wattmeter described on pp. 199 and 209 is equally applicable to either continuous or alternating current circuits, and when used for the former there is no need to take any precautions as regards the inductance of the pressure circuit or the use of metal in its construction. The current coils may also be worked off a shunt, provided a "swamping" resistance of negligible temperature coefficient is connected in series with the coils to avoid temperature errors.

In another arrangement the fixed coils are wound with fine wire and used as the pressure circuit while the moving coil is shunted from the main circuit. This arrangement has the advantage of increased sensitiveness, as it is possible greatly to increase the pressure drop over the winding itself.

The iron-cored wattmeters, as described on p. 219, may also be used for continuous current, the core being magnetised by the pressure of the system and the moving coil worked off a shunt, as for an ammeter. The considerations detailed on pp. 58 and 219 apply in this case also, namely, the importance of keeping the reluctance of the iron portion of the magnetic circuit small, compared with that of the air path. When the pressure is fairly constant, as is usually the case in switchboard work, a horseshoe electro-magnet can be made to give fairly consistent results, but when wide variations of pressure have to be dealt with the hysteristic effect must be reduced, and a construction such as that of Fig. 127 is the most satisfactory.

The moving coil is usually similar in construction to that of a permanent magnet moving coil ammeter, effective damping being obtained by winding it upon a copper or aluminium former. Iron-cored continuous current wattmeters are never entirely free from hysteresis errors, but for measurements requiring ordinary accuracy the results are quite satisfactory. The curve in Fig. 130 indicates what may be expected from

an instrument of the horseshoe magnet type when working under variable voltage conditions such as might occur on a battery charging circuit. Instruments of the form shown in Fig. 127 are capable of much better results. It is always well that the polarity of the instrument should be the same in use as when calibrated, otherwise the whole hysteresis effect due to reversal is introduced.

The most useful applications of such wattmeters are in connection with graphers and large sector type instruments

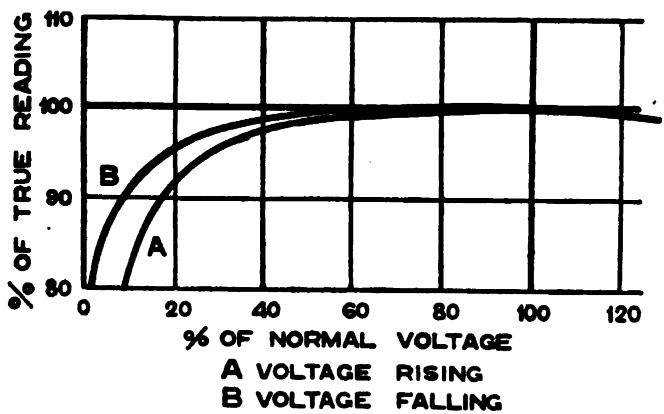


FIG. 130.—Effect of Hysteresis in a Continuous Current Iron-cored Wattmeter.

where particularly large working forces are desirable, on account of pen friction or weight of moving parts.

Induction Wattmeters.

Induction wattmeters are similar in principle to the majority of watt-hour meters now in use for alternating current house service supply, except that the motion is controlled by a spring, while a pointer and scale replace the counting train. In common with induction ammeters and voltmeters (see p. 166), such wattmeters do not lend themselves to extreme accuracy, but are very suitable for switchboard work on account of their robust construction and

long scales. The latter usually subtend an angle of 300°, and are almost evenly divided throughout.

In a general way the **principle adopted** may be said to be similar to that of the induction ammeter or voltmeter of the split-circuit type, except that the two fluxes, displaced in phase, are obtained from the pressure and current respectively instead of by a phase-splitting device.

The elements of an induction wattmeter are shown in Fig. 131, in which PC and CC represent the pressure and

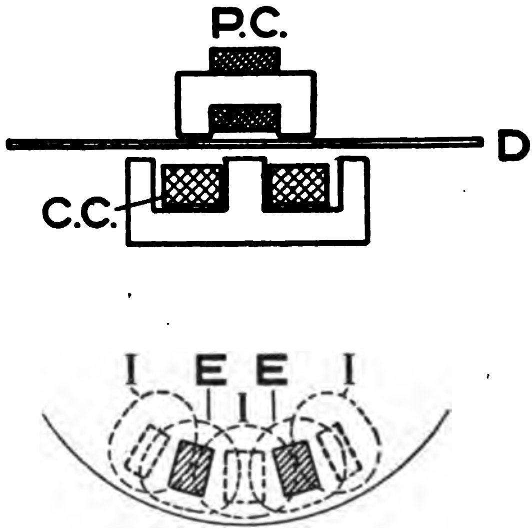


FIG. 131.—Induction Wattmeter.

current coils, respectively, while D is a disc of aluminium, pivoted at its centre, which forms the moving element. The poles of the two electro-magnets (excited by the pressure and current coils respectively) are spaced half a pole pitch apart, so that the pole of one element is opposite the interpolar space of the other.

Considering first the **pressure element,** it is clear that eddy currents will be induced in the disc and will follow paths somewhat as shown at EE, that is, directly across the pole faces of the current element (shown dotted). By design these

eddy currents are arranged to lag 180 electrical degrees behind the pressure applied to the coil PC, and are therefore in phase with the flux due to the current coil CC when the current and pressure of the load are in phase. A torque is thereby produced proportional to the product of these eddy currents into the flux due to the current element, and these two quantities are themselves proportional to the pressure and current, respectively. For power factors other than unity the phase angle φ between the pressure and current of the load is reproduced in the relation between the eddy currents EE and the current flux, so that the effective torque is proportional to $\cos\varphi$ and therefore to the true watts. Similar eddy currents (I) are produced by the **current flux,** and these provide a torque by interacting with the pressure flux. It should be observed that the torque due to each flux acting upon the eddies produced by itself is zero, assuming the self-inductance of the disc to be negligible.

It was shown on p. 167, when dealing with the induction ammeter, that the **torque** was proportional to $f \cdot \Phi_1 \cdot \Phi_2 \cdot \sin\theta$. Similarly, in the case of a wattmeter, we have—

$$\text{Torque} \propto f \cdot \Phi p \cdot \Phi c \cdot \sin\theta,$$

where f is the frequency, Φc the flux due to the current element, Φp that due to the pressure element, and θ the phase displacement between these two fluxes.

The power to be measured is proportional to $I \cdot V \cdot \cos\varphi$. In order, therefore, that the torque may be proportional to the power, it is necessary to make—

$$\Phi c \propto I \quad \ldots \ldots \quad (1),$$

$$\sin\theta = \cos\varphi \quad \ldots \ldots \quad (2),$$

and

$$f \cdot \Phi p \propto V \quad \ldots \ldots \quad (3)$$

Since the air-gap of the current element is considerable and the flux density is kept low, it may be assumed that $\Phi c \propto I$, throughout the working range, which is the first requirement above.

In Fig. 132 is shown the general relationship between the

main current A, applied pressure V, current flux Φc and pressure flux Φp. The phase displacement of the load is φ, and the angle between the fluxes θ. The current flux will lag behind the main current by a small angle, α, owing to hysteresis and eddy currents. In order that *sin* θ may be equal to *cos* φ, which is the second requirement, we must have $\theta = 90 - \varphi$, and this will be the case if in Fig. 132 the angle between V and Φp is made equal to $90 + \alpha$.

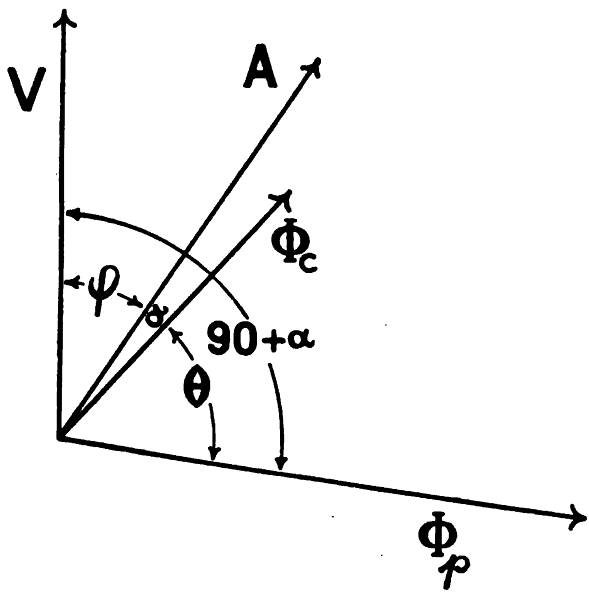


FIG. 132.—Induction Wattmeter Pressure and Current Element Vectors.

It is not possible, with a simple magnet such as that shown in Fig. 131, to obtain a lag of more than about 80°, and some compensating device is essential. One of the most common is shown in Fig. 133. The flux in the central core divides into two parts, of which one returns through the air-gaps LL, and the other passes through the lagging ring R, disc D, and soft iron tongue J.

Fig. 134 shows, in an elementary way, the **relationship**

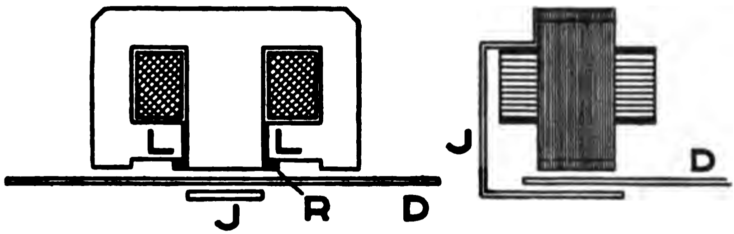


FIG. 133.—Pressure Element and Induction Wattmeter.

between the various quantities.[1] The flux Φ in the central core divides into an unlagged portion, Φ_1, passing through the air-gaps LL, and a lagged portion (the working flux), Φp,

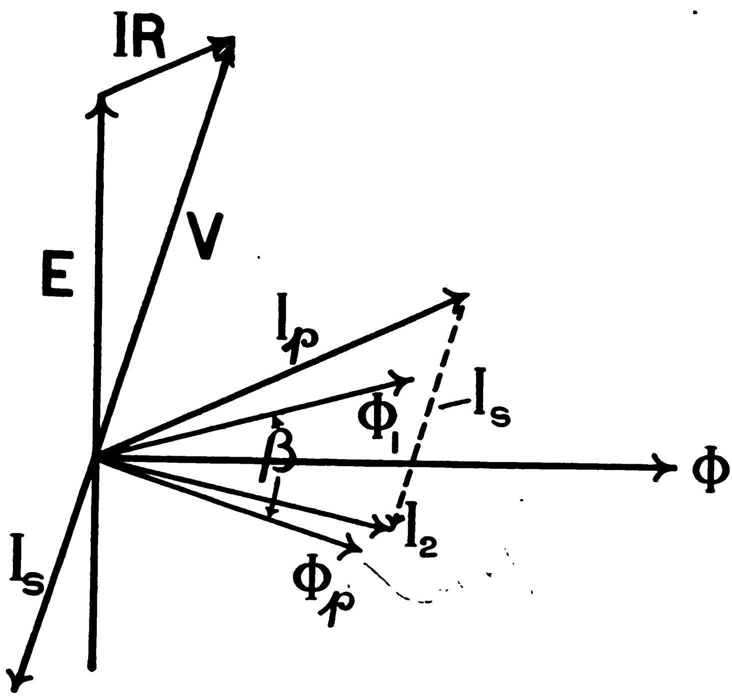


FIG. 134.—Vector Diagram for Pressure Element of Induction Wattmeter.

[1] For a more detailed discussion see "Theory and Operation of the Split Phase Magnet," by F. Hymans, *Electrical World*, Vol. 68, pp. 1000 and 1192, also *Electrician*, Vol. 78, p. 638 (1917).

passing through R, D, and J. This latter flux induces a secondary current, I_s, in the ring R, so that the magnetising current available for Φp is I_2 (the resultant of I_p, the current flowing through the winding, and I_s). The fluxes Φ_1 and Φp will lag behind their respective magnetising currents, I_p and I_2, by small but not necessarily equal angles.

It was shown previously that the angle between V and Φp must be made equal to $(90 + a)$ (Fig. 132), and this angle can readily be adjusted by varying the current I_s, as will be clear from Fig. 134. This can be done either by varying the resistance of the ring R, which may consist of a few turns joined through an adjustable resistance, or by changing the value of Φp by moving the lower extremity of the tongue J towards or away from the disc. It should be observed that the effect of eddy currents in the disc D is the same as that of those in the ring R, so that I_s actually corresponds to the sum of the two.

The main flux Φ linking with the winding on the central limb induces an E.M.F. (E) in it. The impressed voltage V has to overcome this E.M.F., as well as to provide for the ohmic drop IR. It will be seen from the figure that for small changes of frequency and pressure Φp is proportional to Φ, so that we have—

$$E \propto f \,.\, \Phi \propto f \,.\, \Phi p,$$

also under the same conditions $V \propto E$, and consequently

$$V \propto f \,.\, \Phi p,$$

which is the third condition to be fulfilled.

Hence it follows that the torque is proportional to the watts.

Without any compensation a lag of about 80° can be obtained (between V and Φp), and the remaining lag can be produced by other means. For example, split circuits may be employed for either pressure or current windings, so as to cause the effective part of the former to lag or of the latter to lead. Thus, if the pressure magnet M. (Fig. 135) is shunted by a non-inductive resistance, R, and

connected in series with a choking coil, CC, the current through the magnet winding will lag behind the whole current through the choking coil, and may thus be made to lag fully 90° behind the applied pressure.

Again, by connecting a non-inductive resistance in series with the current coil and shunting both resistance and coil by an inductance the current in the magnet winding may be made to lead the main current, so that the flux due to the current element can be brought into exact quadrature with that due to the pressure element. These devices, however, are not much used at the present day, the eddy current method of compensation being much more general.

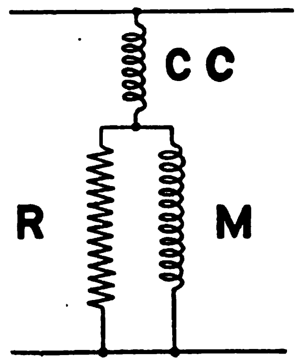


FIG. 135.—Phase Compensation in Induction Wattmeter.

Another matter of importance in the design is the provision of a perfectly symmetrical field, or there will be a tendency for the instrument to give a deflection in one direction or the other when **subjected to either pressure or current excitation alone.** The effect is, in fact, similar to that of a shaded pole induction ammeter or voltmeter. The adjustment may be made either by moving the current element laterally with reference to the pressure element or, if the iron tongue type of compensator is employed (J, Fig. 133), by moving this. Or, again, an aluminium or copper vane is often placed in the gap between the magnet pole and disc, so that it can be moved to one side or the other for the same purpose.

The **effect of changes of frequency** is, roughly, as follows:—

Since the air-gap of the current element is large and the induction low, Φ_c (Fig. 132) is almost independent of frequency. The main flux Φ (Fig. 134) is proportional to E/f, so that for a given applied voltage, Φ is proportional to $1/f$. Consequently, as a first approximation, Φ_p, and with

it I_2, may be assumed to be proportional to $1/f$, and, consequently, I_s to be constant. Hence it follows that an increase of frequency causes a relatively greater reduction of I_2 than of I_p, with a consequent decrease of $f \cdot \Phi_p$. For the same reason a rise of frequency causes an increase of β, and with it of θ (Fig. 132).

From this it follows that, with increasing frequency, Φ_c is constant, $f \cdot \Phi_p$ decreases, while $\sin\ \theta$ may decrease or increase according to the phase relationship between V and A. Consequently the torque may either increase or

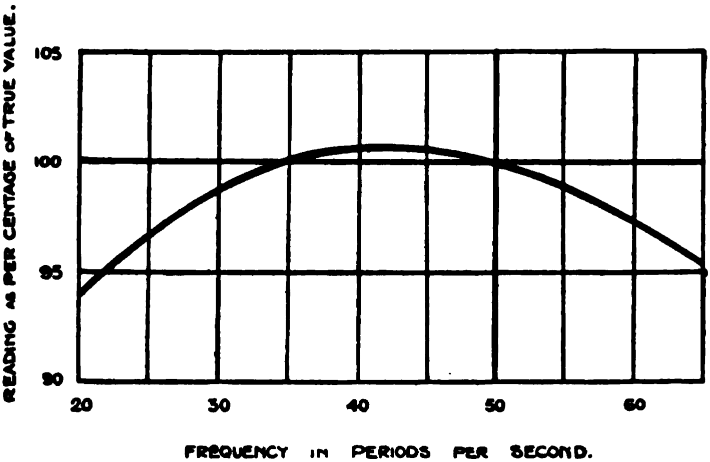


FIG. 136.—Effect of Frequency Variation on Induction Wattmeter.

decrease with rise of frequency according to the power factor of the load. For example, at or about unity power factor θ is approximately 90°; consequently moderate changes of β are almost without effect upon $\sin\ \theta$, and the influence of the term $f \cdot \Phi_p$ is predominant, so that the torque increases with a fall in frequency. If the frequency is lowered beyond a certain point, however, the decrease of β, and with it of θ, is sufficient to cause the decrease of $\sin\ \theta$ to more than counterbalance the increase in the term $f \cdot \Phi_p$, so that the torque decreases with falling frequency.

This is well seen in Fig. 136, which shows the connection

between frequency and reading in the case of a 50-cycle wattmeter on a load of unity power factor. Above 45 cycles the torque rises with decreasing frequency. Between 40 and 45 cycles it is almost constant, and below 40 cycles it falls off with decreasing frequency.

With a lagging current a reduction of frequency gives a lower reading owing to θ becoming smaller, whilst with a leading current the effect is reversed, owing to θ becoming

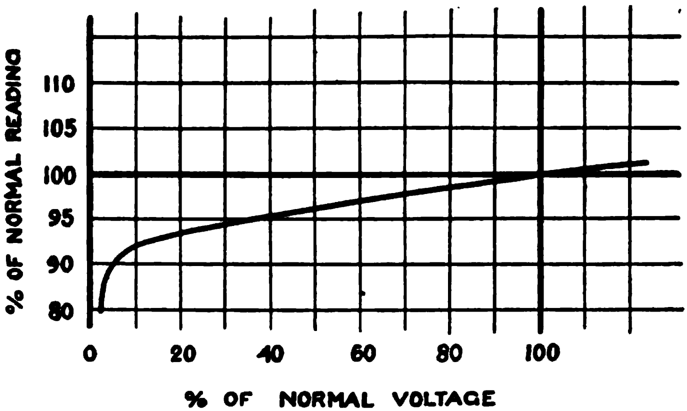


FIG. 137.—Effect of Voltage Variation on Induction Wattmeter.

more nearly equal to 90°. Changes of wave form are in general negligible in their effect upon the readings.

Owing to saturation of the iron, which causes a want of proportionality between Φ and I_p, Φ_p increases at the expense of Φ_1 as E is increased. Consequently the indications are not altogether independent of the pressure, but increase slightly with it. This is seen from the curve in Fig. 137.

It should be noticed that the scale of a wattmeter does not follow a "square law," the reading being, in fact, directly proportional to the torque, instead of to $\sqrt{}$ torque. Consequently a 1 per cent. change of torque is accompanied by a 1 per cent. change of reading, instead of $\frac{1}{2}$ per cent., as in the case, for example, of an induction ammeter or voltmeter (see p. 169).

For this reason, the wattmeter is, of all induction instruments, the most **affected by temperature.** It is extremely difficult to compensate for the high temperature coefficient of the aluminium or copper disc, and the torque is inversely proportional to its resistivity. The temperature coefficient is usually from 0·2 to 0·4 per cent. per degree Centigrade change of temperature, the instrument reading low with increase of temperature, and *vice versâ*. The error due to self-heating[1] is usually small, however, and is negligible in a well-designed instrument.

A simple means for avoiding both forms of temperature error might appear to lie in the use of an alloy having a negligible temperature coefficient, for the construction of the disc, but it is found in practice that, on account of the enormous increase in the disc resistance which would be involved with any such alloy at present known, this proposal is impracticable. An alloy possessing high conductivity combined with lightness and a negligible temperature coefficient would be extremely valuable for this and many similar purposes (see p. 176).

It may be pointed out that the temperature error in an induction watt-hour meter of corresponding construction is inherently much less than that of a wattmeter. This is owing to the fact that in the former case both the retarding and the driving torques depend upon eddy currents in the same disc, so that the two effects cancel out. With the wattmeter, on the other hand, the control is almost independent of temperature.

The **damping** is usually carried out by a permanent magnet acting on the same disc as that used to produce the deflectional torque, and can be made very effective. For a discussion of the best position for both damping magnets and driving electro-magnets on the disc see pp. 42 and 175.

In **polyphase induction wattmeters** two (or three) com-

[1] In testing induction instruments for temperature and self-heating errors, there is difficulty in obtaining accurate observations on account of the great time lag. For temperature tests it is usually necessary to have the surrounding temperature constant for something like three hours before taking a reading, if the results are to be relied upon.

plete single phase elements may be assembled about the same disc. There is then no necessity for increasing the depth of the instrument, as in the case of the dynamometer pattern, where the separate elements are built up one over the other upon the same spindle. This is a decided advantage but care must be taken that the elements are not placed so close together that the eddy currents from one pass into the field of the other, or serious interference will result.

Electrostatic and Hot Wire Wattmeters.

Besides the dynamometer and induction types of wattmeter, several others have been suggested from time to time, but have not been successfully developed for industrial purposes. The most important are the electrostatic wattmeter originated by G. L. Addenbrooke[1] and the hot wire wattmeter due to M. B. Field.[2]

The **electrostatic wattmeter** has attained some considerable importance on account of its adoption by the National Physical Laboratory as a final standard of reference.[3] For this purpose its valuable characteristics are—(1) enormous range, together with (2) almost complete freedom from errors due to changes in the surrounding physical conditions and (3) freedom from errors due to ordinary changes of frequency or wave form. The instrument consists of a quadrant electrometer charged heterostatically (see p. 185) by applying the voltage drop, due to the main current passing through a shunt, between the quadrants, while the circuit pressure is applied between the suspended vane and one of the quadrants.

The connections are as shown in Fig. 138, in which A is the suspended vane and B and C are the pairs of quadrants. The shunt, which must be perfectly non-inductive, is shown at S. Then, writing V for the instantaneous pressure between A and C and v for the pressure drop over the shunt (which is

[1] *Electrician*, Vol. 14, p. 901 (1900), and Vol. 51, pp. 811, 845 (1903).
[2] *Electrical Review*, Nov. 25th and Dec. 2nd, 1898.
[3] Paper by Paterson, Rayner, and McKinnes, *Journal Inst. E.E.*, Vol. 51, p. 294.

the same as the potential difference between B and C), the deflecting couple is equal to—

$$a\,(V \pm v)^2 - bV^2.$$

The first portion of this expression represents the force of attraction between A and B, and the second that between A and C. The factors a and b are constants depending upon the dimensions of the instrument and the angular position of the needle with reference to the gap between the fixed vanes.

Resolving this expression, the torque is—

$$(a - b)\,V^2 \pm 2aVv + av^2.$$

The first term might be reduced to zero if the values of

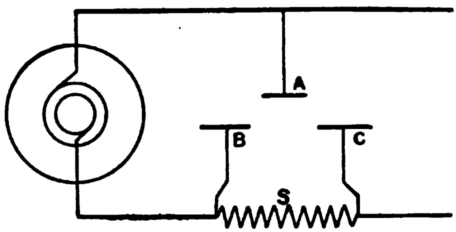


FIG. 138.—Electrostatic Wattmeter.

a and b could be made precisely equal. In order to approximate to this condition, the gap between the fixed vanes B and C must be made as small as possible, so that the moving vane is practically working within a cylindrical metal box coaxial with the suspension. In practice this factor causes the reading to be slightly different for the same amount of power under varying voltage conditions. The second term in the expression is simply proportional to the power flowing, and is positive or negative according to whether the potential between A and B is greater or less than that between A and C. The third term is usually negligible, since v is small compared with V. This term represents the power lost in half the shunt, and should be taken into account for accurate work.

The instrument therefore acts as a true wattmeter when

used at constant voltage, but is not entirely independent of voltage variations. Careful screening is essential to obviate disturbance by the presence of charged bodies in the neighbourhood. The great obstacle, however, to the use of the electrostatic wattmeter for any but laboratory measurements, lies in the fact that unless a very considerable drop of voltage is permitted on the shunt, the instrument is necessarily very insensitive.

It has been proposed by E. Wilson and Highfield to overcome this latter difficulty by using, in place of the shunt, a form of current transformer of which the secondary consists of a rotating air-cored armature with a large number of commutator segments. The primary winding acts as the field coil, and the armature, which is run at a carefully measured speed, produces an E.M.F. of any desired value and proportional at every instant to the current flowing through the primary winding. It cannot be claimed that this arrangement is a particularly accurate one, but it might prove useful for the direct measurement of very large amounts of power at high pressures.

The **hot wire wattmeter** is of scientific rather than of practical interest. It consists essentially of a double hot wire instrument arranged so as to measure the difference of extension of two wires. By an arrangement of shunts and transformers one of the wires is made to carry a current proportional to the sum of the pressure of the system and the drop over a shunt, while the other carries a current which depends on the difference of these two quantities. Thus, calling V the instantaneous pressure of the system and v the drop over the shunt, the reading is a function of $(V + v)^2 - (V - v)^2$, *i.e.*, of $4\ V.v$, which is proportional to the power.

Hot wire instruments are always somewhat insensitive, and since the wattmeter does not use the whole extension of the wire, but only the difference in the extension of two wires, it is still more deficient in this respect. It also necessarily suffers from the defects common to all hot wire instruments, such as creeping of the reading, change

of zero, sluggishness, etc. There seems to be no reason why this principle should not equally well have been applied to the moving iron or induction types of instrument.

Idle or Reactive Component Meters.

It is often useful to be able to measure directly the idle component of the volt amperes in an alternating current circuit. The factors which multiplied together equal the true power are the pressure, the current, and the cosine of the angle of phase displacement, so that under constant voltage conditions it is occasionally useful to consider the product of the current into this cosine as representing the power component of the current. Similarly one might refer to the product of the current into the **sine of the phase displacement** as the idle component, since this is the amount which must be added vectorially to the power component in order to obtain the actual current flowing. The product of pressure, current, and sine is sometimes referred to as the reactance "power" for want of a better name, although the quantity has no connection with rate of doing work.[1]

Instruments, which are variously described as "idle current ammeters," "wattless power meters," "reactance power meters," or, erroneously, "power factor meters," serve to determine the idle or reactive component of the current or volt amperes, and are therefore better described as "idle or reactive component meters."

As an example of the use of these idle component meters it may be mentioned that when the power factor of an alternating circuit is low it is a common expedient to instal an over-excited synchronous motor or an induction motor with a phase-compensating device, to improve the power factor. The sole function of such machines is then to supply sufficient idle current, and it is useful to instal an idle current or reactive component meter to correct the power factor. All that is required is an instrument which will read zero when the power factor is unity.

[1] The cosine and sine of the phase difference are spoken of as the "power" and "reactance" factors respectively.

For this purpose a dynamometer wattmeter may be used with a condenser or choker [1] in place of the usual potential circuit non-inductive resistance, so that it takes a current which leads or lags by 90 electrical degrees. If, then, the power factor of the circuit is represented by *cos* φ, such an

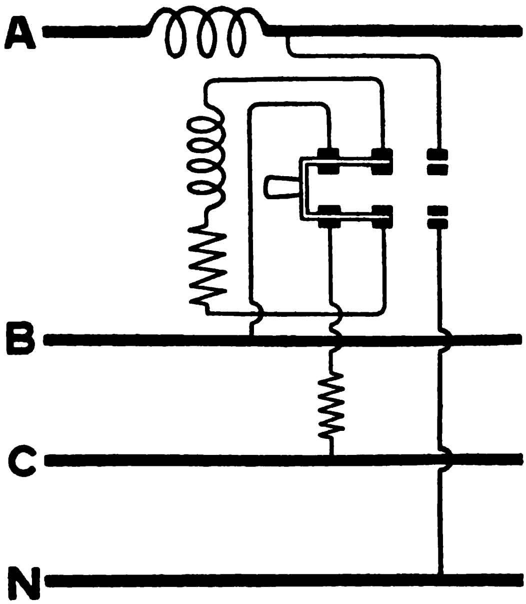


FIG. 139.—Wattmeter arranged to measure True or Reactive Power, at Will.

instrument will read $E \times I \times cos . (90 - \varphi)$, *i.e.*, $E \times I \times$ *sine* φ.

Another arrangement, suitable for **three-phase circuits,** utilises the angular displacement between the phases by exciting the pressure circuit of a true wattmeter from the two lines opposite to the one in which the current coil is inserted. This arrangement is equally applicable to either induction or dynamometer type instruments. The connections are shown in Fig. 139. By means of the switch the same

[1] If a choker is used, an additional phase-splitting shunt in parallel with part of the potential circuit is required in order to obtain exact quadrature (see p. 231 for a similar arrangement).

instrument may be made to indicate either the true power or the reactive component at will.

The scales of idle component meters may be calibrated in terms of either the idle component of the volt amperes or of idle current at the pressure of supply. In the former case the readings will be comparable with those of any wattmeters in the circuit, and in the latter (which is more widely used) with those of the ammeters.

The use of idle component meters is becoming obsolete, since a direct reading power factor meter is far more convenient.

Phase or Power Factor Meters.

To obtain a clear understanding of what is happening in an alternating current circuit, it is essential to have an instrument which indicates directly the phase angle between the pressure and current, and that independently of the magnitude of either of these quantities. Such an instrument, if calibrated in terms of the cosine of this phase angle, may be termed a power factor meter [1] or, if in terms of the sine, a reactive factor or idle component meter (see also p. 238).

Single Phase Power Factor Meters.—In describing the ohmmeter principle on p. 103, it was shown that the position taken up by the pivoted needle (Fig. 50) is dependent upon the relative magnitudes of the currents in the two sets of coils. As an alternative, the magnetised needle *n* may be replaced by a pivoted coil supplied with current by ligaments so flexible that the coil can be regarded as free from all mechanical control. Such an arrangement, if excited by continuous current, will behave in the same way as the device shown in Fig. 50. If, now, the various coils are excited with alternating current, a similar result is obtained,

[1] When the pressure and current waves have different wave forms, the power factor may be defined, either, as $\frac{\text{true power}}{\text{apparent power}}$ or as the cosine of the angle of phase difference between crest or zero values of current and pressure. The difference between these expressions is negligible in most cases which occur in modern practice.

except that the position taken up will depend upon the components of the currents in coils *a* and *b*, which are in phase with the current in the coil *n*, and not on their total values. By so arranging matters that the currents in *a* and *b* differ in phase, but bear a constant relation to each other in

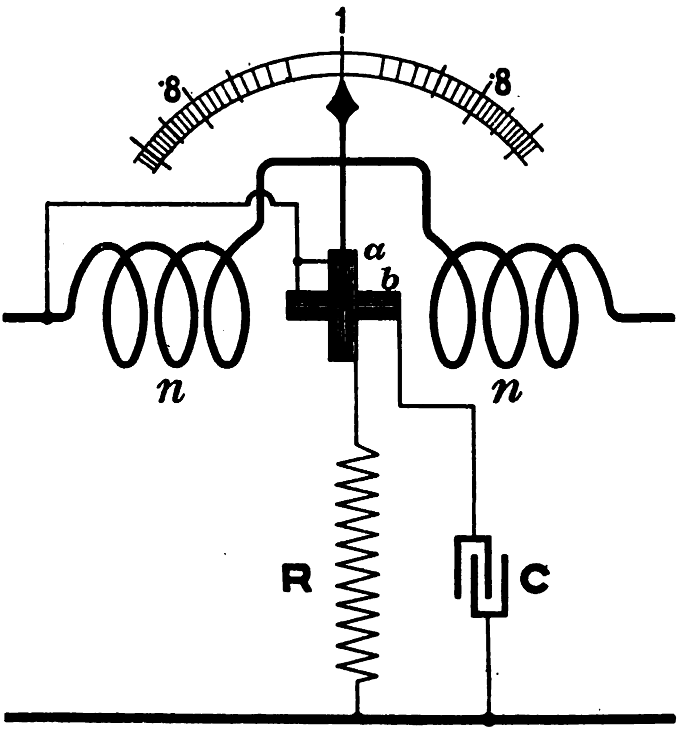


FIG. 140.—Single Phase Power Factor Meter.

magnitude, an instrument is obtained in which the angular position taken up by the coil *n* depends only on the phase difference between the current in it and that in the coils *a* and *b*.

In the practical instrument (Fig. 140) the coils *a* and *b* are connected across the mains through a high resistance, and for this reason are mounted on the moving element,

while a phase-splitting device consisting of a non-inductive resistance, R, in series with *a*, and a condenser, C, or choker, in series with *b*, produces a phase difference of nearly 90° between the currents in the two coils. The coils *n* are fixed and carry the main current, or are connected to the secondary of a current transformer. It will be seen that when the main current is in phase with the pressure it is also in phase with the current in *a* and in quadrature with that in *b*. The moving system will therefore take up the position shown in the figure, since no torque is experienced by the coil *b*. The opposite occurs when the power factor of the load is zero, since under these conditions the current is 90° out of phase with the pressure and therefore in phase with the current in *b*, while in quadrature with the current in *a*. It therefore follows that the moving system will turn until the coil *b* is in line with the current coil *n*, since coil *a* experiences no turning moment. For any other phase relationship the moving system takes up some intermediate position.

It will thus be seen that, for a change of 90 electrical degrees, the pointer of the instrument moves through a right angle and may readily be calibrated to show the displacement throughout the whole 360°. Fig. 141 shows the scale of a phase meter calibrated in this way which has been marked both in phase angles and in the corresponding power factors. It will be noticed that in the scale illustrated the electrical angles are shown by corresponding geometric angles, so that the circle is divided equally into 360 electrical degrees. To attain this end, the coils *a* and *b* must be electromagnetically equal, and some care is required in the shaping of the various windings. In addition, *a* and *b* must be set precisely at 90° to each other, and their currents must be in strict quadrature. Such a scale is, generally speaking, the best form for laboratory use, but for switchboard instruments it will often be found desirable to modify the scale shape, somewhat.

The actual angle between the coils and also the lag or lead of the current in the coil *b* are unimportant provided the scale is empirically calibrated, but considerable scale

distortion occurs unless the spacing bears a correct relation to the phase difference between the currents. Using a condenser in circuit *b*, there is no difficulty in obtaining almost exactly 90° phase displacement, so that a symmetrical scale is obtained by setting the coils *a* and *b* at right angles. When a choking coil is used, the maximum phase displace-

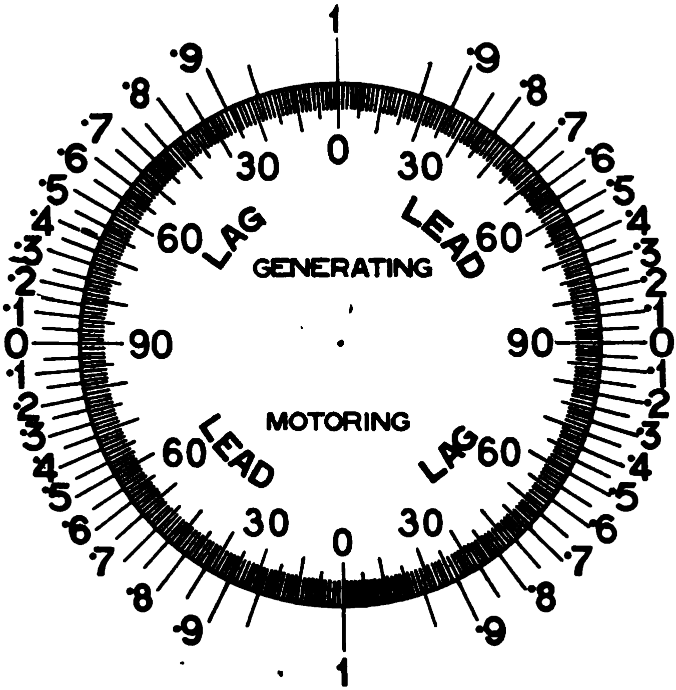


FIG. 141.—Scale of Phase Meter.

ment obtainable is not much more than 80 electrical degrees, and it will be found that this arrangement, with the rotor coils set at right angles, results in a scale shape which is cramped on the "lag" side and extended on the "lead" side. This defect may be overcome by modifying the spacing of the rotor coils,[1] but it may be said that, in general, the use

[1] The coils may be set at the same geometric angle to each other as the electrical angle between the currents, if this is other than 90°.

of a condenser with right angle spacing of the coils is the best arrangement.[1]

It is obvious that, whether a condenser or choking coil is used, the instrument reading will be **affected by frequency and wave form.** The main application of such instruments therefore is for switchboard use, where both can be regarded as constant.

Where it is desired that the instrument shall be independent of frequency, the arrangement illustrated in Fig. 142 may be used.[2] This consists in dividing the coil *b* (Fig. 140)

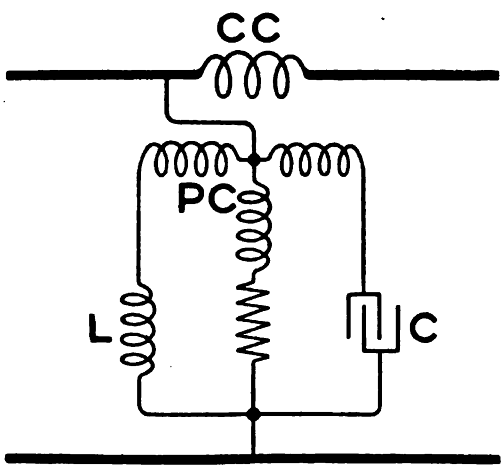


FIG. 142.—Single Phase Power Factor Meter compensated for Frequency.

into two halves and connecting one half in series with a condenser, C (Fig. 142), and the other with a choking coil, L. The connections are so made that the electro-magnetic effects of the two coils are in the same direction, though the currents are displaced by approximately 180°. These currents are adjusted to equality at the mean frequency

[1] Objection has been raised in the past to the use of condensers on the score of their being liable to sudden failure and to variations in the course of time. Such criticisms do not apply to modern condensers, such as those made by the Mansbridge process.

[2] L. Murphy, *Electrician*, April 17th, 1914, " A single phase power factor meter for use on variable frequency."

on which it is intended to employ the instrument. A rise of frequency causes a proportionate increase in the condenser current, but it also produces a decrease in the choker current, so that the total ampere-turns of the two coils tend to remain approximately constant over a wide range of frequency. If the upper limit of frequency is not more than 50 per cent. above the lower, it can be shown that the greatest error introduced will not exceed 1·5 electrical degrees.

For polyphase circuits it was first proposed by **Punga** to utilise the actual angular displacement of the phases to excite the pressure circuits and thus avoid the necessity for any phase-splitting device while at the same time obtaining complete independence of frequency and wave form.

It may be observed that the arrangement of right angle coils with a phase-splitting device, as just described, has the effect of producing a rotating field, and this may be achieved equally well on a polyphase system by spacing the requisite number of rotor coils at angles which correspond with those of the phases to which they are connected. Thus a rotor with coils at right angles, as already described, may be used on a two-phase system if the current coil carries the current in one of the lines, and each rotor coil is connected through a suitable high resistance across one of the phases. For three-phase circuits the arrangement is shown in Fig. 143. The main current flows through the coil CC. In the field of this, is pivoted the rotor carrying the pressure coils VC, much as in a dynamometer wattmeter, except that there are three such coils, spaced 120° apart. Each coil is connected through a high resistance, R, to one of the mains, and, as the resistances of these three paths are made equal to one another, the common junction of the coils forms an artificial "neutral point."

This instrument measures the phase angle between the current in the line including CC and the pressure between that line and the neutral point. The readings are quite independent of wave form or frequency, but it is only

strictly applicable to **balanced loads,** since the readings refer to one line alone. Slight inaccuracies will also be introduced if the voltages between the three lines are not symmetrical, as this affects the phase distribution of the currents in the three rotor coils.

For **unbalanced loads** the arrangement shown in Fig. 144 can be used. In this case the three line currents pass through a system of fixed coils (CC_1, CC_2, and CC_3) spaced 120° apart, similarly to the three rotor coils VC. This construction is

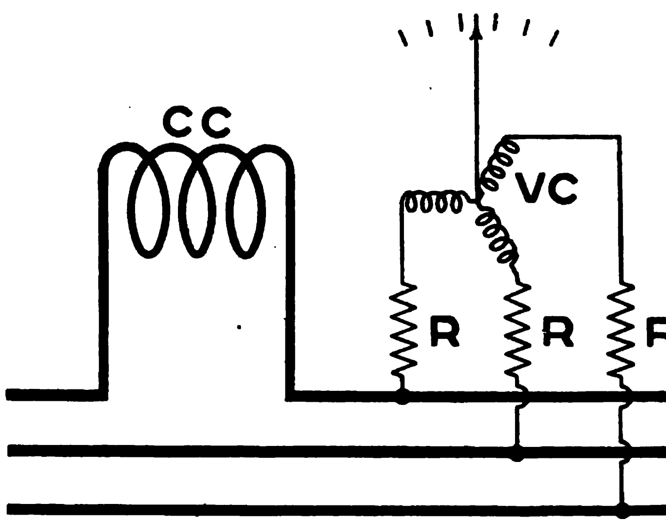


FIG. 143.—Three-phase Power Factor Meter for Balanced Loads.

actually equivalent to three balanced load power factor meters having a common moving system, so that it gives an average result for the power factor of the three phases. But this average is more than simply the arithmetic mean of the three figures representing the power factor of each line as measured on a balanced load instrument.

In Fig. 145 let I_1, I_2, and I_3 represent the currents in the lines of a three-phase four-wire system, and E_1, E_2, and E_3 the corresponding pressures between line and neutral point, the phase angles between these quantities being shown by

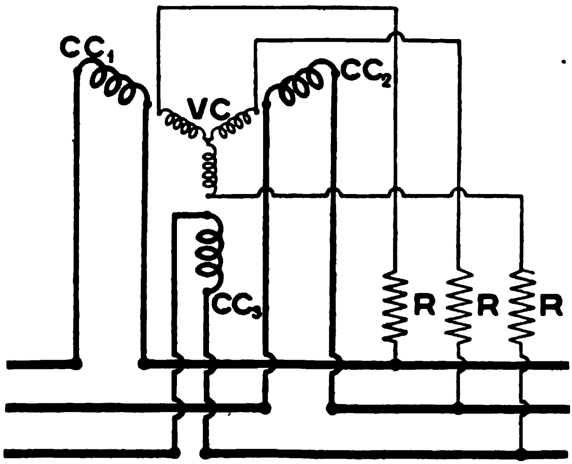


FIG. 144.—Three-phase Power Factor Meter for Unbalanced Loads.

φ_1, φ_2, and φ_3, respectively. The construction of Fig. 146 will now give the average phase angle as shown by an

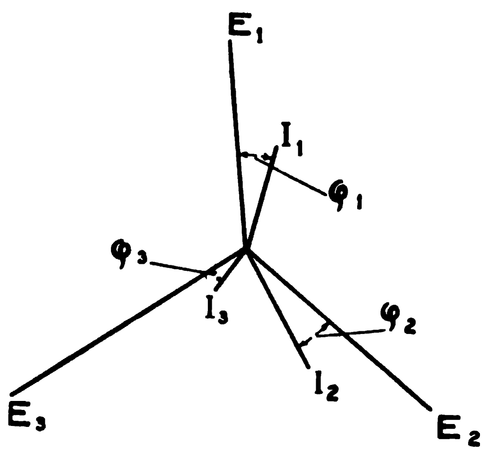


FIG. 145.—Vector Diagram of Three-phase Load.

unbalanced load instrument such as that described. From O the current I_1 is drawn, making an angle φ_1 with the horizontal. The current I_2 is now set off from the end of I_1

at its own angle, φ_2, with the horizontal. Finally, I_3 is added in a similar manner from the end of I_2. In this construction lagging currents have been shown by lines sloping upwards from the horizontal and leading currents by lines sloping downwards. The average phase displacement of the current in the whole system with reference to the line voltage to neutral is then found by joining the origin O to the end of I_3, giving the angle φ. The cosine of this angle may be taken as the power factor of the system. Stated in words, it may be said that the instrument reads the average phase displacement of the current with reference to pressure, taking into account the relative magnitudes of the three line currents.

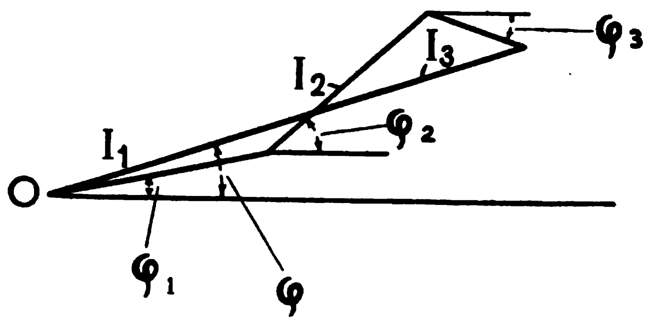


FIG. 146.—Diagram for Unbalanced Load Power Factor Meter.

Dynamometer power factor meters are also constructed for working on two or three-phase balanced loads, employing a **single pressure coil and two or three current coils**, respectively, to produce the rotating field, as in the unbalanced load type just described. It may usually be assumed that the pressures between the various lines are equal, but even on so-called balanced loads a slight inequality in the line currents often exists. The phase meter with a single pressure coil is very sensitive to any such inequality, which introduces a serious error. It follows that the pattern employing a single current coil and three pressure coils is more accurate and much to be preferred. The only advantage possessed by the alternative arrangement is that

current transformers are cheaper than pressure transformers.

Another form of power factor meter is that due to Conrad and known as the **inductor[1] or moving iron type.** The construction of this instrument, for three-phase balanced loads, is illustrated in Fig. 147, and is similar in principle to the synchroniser described on p. 287 (see Fig. 177). In

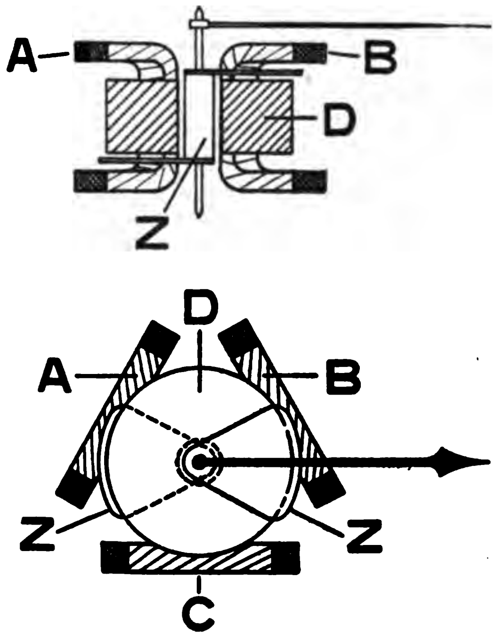


FIG. 147.—Moving Iron Three-phase Power Factor Meter.

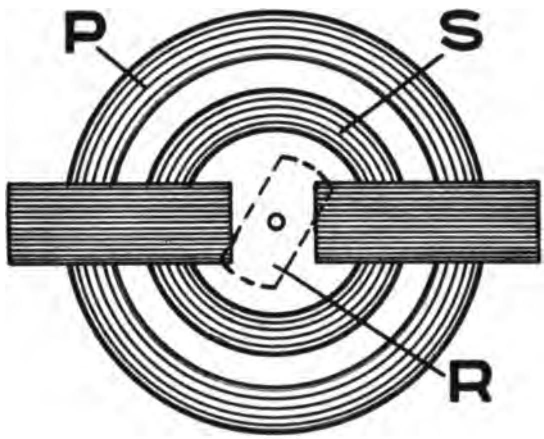
Fig. 147 A, B, and C are three coils carrying the line currents, spaced 120° apart, and thus producing a rotating field. The centre coil D, which is also fixed, is wound with fine wire, and is connected, either directly or through a resistance, across one of the phases, thereby magnetising the pivoted iron Z. The action of this instrument is similar to that of the simple dynamometer form, except that all movement of the centre

[1] Often loosely referred to as the "induction" type.

coil is obviated. It will be observed that the turning of the pivoted iron Z through a given angle has the same effect as turning the coil D through the same angle, if it were mounted on the spindle with its magnetic axis at right angles to it. When it is essential that the indications of the instrument shall extend over a complete circle this form of meter is useful, since it is evident that the simple dynamometer type is limited in its travel by the ligaments employed to lead current into the rotor coils. Such a case arises when an alternating to continuous current converter is required to transform sometimes in one direction and sometimes in the other.

Unfortunately, the inductor type possesses some drawbacks which render it less accurate than the dynamometer, although good enough for switchboard use. On account of eddy currents and hysteresis in the moving iron, there is a rotational drag exerted on it by the rotating field. This drag increases with the frequency, and is approximately proportional to the square of the current in the field coils A, B, and C. As the torque which is available for holding the moving system to its reading is proportional to the current, it follows that the drag produces a greater error at the heavier loads. If the alternative is adopted of exciting the coils A, B, and C from the pressure of the system, it will be seen that the drag torque becomes constant for all loads, but the working torque necessarily varies with the current. Thus with either arrangement the readings are liable to be affected by the magnitude of the load, and the only safeguard consists in a reduction of the drag by careful design. Of the two alternatives, a current-excited rotary field is the most satisfactory, but cannot well be used for a single phase meter. In this case the coils A, B and C are replaced by two pairs of coils spaced 90° apart and pressure excited through a phase-splitting device, as already described. The inductor principle has not been successfully applied to the construction of unbalanced load power factor meters.

Another proposal for obtaining a continuous scale consists in replacing the ligaments in the dynamometer pattern by a



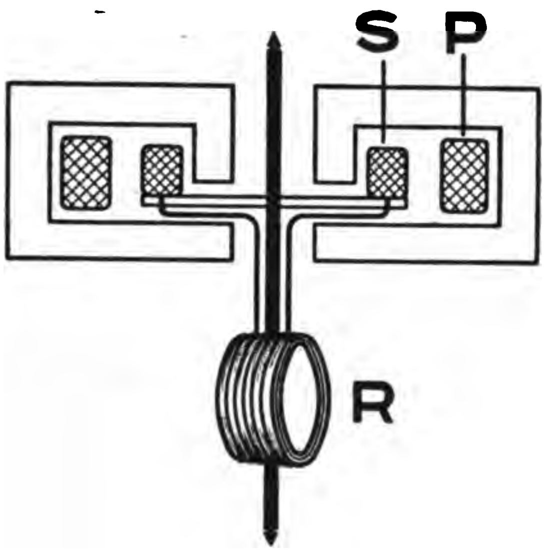


FIG. 148.—Transformer Pattern of Power Factor Meter.

transformer coupling,[1] as shown diagrammatically in Fig. 148. The construction of the dynamometer part of this meter

[1] For a description of some work on an instrument of this type see articles by R. D. Gifford, *The Electrician*, April 16th, 23rd, and 30th, 1915.

is similar to that of instruments using ligaments (see p. 241). The inductive coupling consists of a small transformer with circular primary and secondary coils, P and S, mounted concentrically about the spindle O. The primary coil P is fixed, and the secondary S is carried by the spindle and supplies current to the rotor coil R. An iron yoke surrounds both coils so as to reduce the reluctance of the magnetic circuit, but an air-gap is essential to permit the supports of the coil S to pass through to the spindle. The primary of the transformer can usually be wound for direct connection across the supply pressure without any additional resistance.

For unbalanced load circuits two or three rotor coils are required, and it is necessary to employ two or three of these transformers. It is usually possible to limit the number to two, since for three-phase working the third rotor coil can be supplied by the resultant pressure across the ends of two transformers connected as shown in Fig. 149.

This form of power factor meter appears to be applicable to most requirements, but it is questionable whether the extra complication and greatly increased weight are justifiable, except for unbalanced load instruments in which a continuous scale is essential. The accuracy is less than that of the simple dynamometer pattern, and the readings are slightly affected by frequency variations. Another rather serious disadvantage lies in the fact that the weight on the pivots is very large, while the working forces are no greater than in the case of the simple dynamometer type.

Iron-cored Phase Meters.—With a view to reducing the errors caused by stray fields and to increasing the working forces, it was shown by Sumpner[1] that the dynamometer type of power factor meter could be built with its magnetic circuit partly of iron. In this construction the current coils are wound in slots on the inner surface of a laminated ring, somewhat like the stator of a miniature induction motor. Within this, and concentric with it, is a cylindrical laminated core. There is a narrow annular air-gap between

[1] "The Use of Iron in Alternate Current Instruments," *Journal Inst. E.E.*, Vol. 34.

the two, and in this gap is pivoted the moving coil (or coils), connected in series with a high resistance across the mains. The general arrangement of coils is similar to that of the air-cored instruments already described, but considerable mechanical difficulties arise when arranged for unbalanced loads.

An ironclad power factor meter can also be constructed on the lines of the wattmeter illustrated in Fig. 127, the single pivoted coil being replaced by two or three coils, as the case

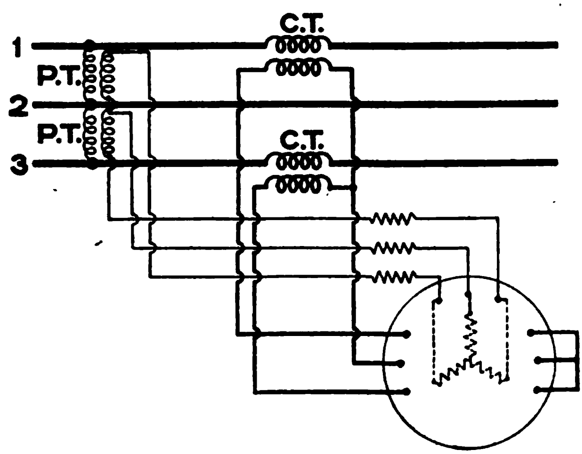


FIG. 149.—Connections of Three-phase Unbalanced Load Power Factor Meter.

may be, appropriately spaced. This instrument, also, is suitable for balanced loads only.

Connecting up Power Factor Meters.—Single phase instruments present no special difficulties, the connections being very similar to those of the corresponding wattmeter. Polyphase instruments, particularly of the unbalanced load type, are apt to cause some difficulty to those unfamiliar with them. The connections for a three-phase unbalanced load power factor meter working off two current and two potential transformers are shown in Fig. 149. Of possible mistakes, the commonest are—

1. Incorrect polarity on one or more transformers.

2. Phase rotation not taken into account with reference to either pressure or current terminals or both.

Most manufacturers mark the terminals of their transformers in such a way that the secondary pressure or current is a copy of the primary in direction as well as magnitude, so that the diagram in Fig. 149 would apply to a direct connected instrument if the transformers were eliminated and the terminals connected direct to the lines. The markings should be carefully observed when connecting up, but if an error is made it may be traced from its effects, as follows:—

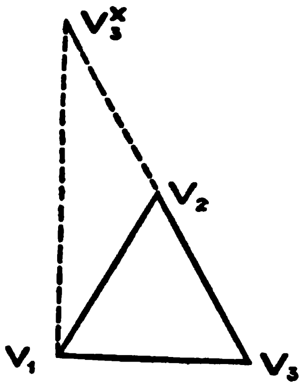


FIG. 150.—Reversal of Potential Transformer Secondary.

(*a*) Reversal of secondaries of all transformers, that is of current *and* potential leads, has no effect.

(*b*) Reversal of all current *or* all potential transformers, but not of both, causes complete reversal of the instrument readings.

(*c*) Reversal of *one* transformer only results in an unbalancing effect in the secondaries, and for this reason it is advisable, if possible, to check the values of the currents and potentials of the secondary windings. With the arrangement shown in Fig. 149 it will be seen that a reversal of one potential transformer secondary will produce the effect shown vectorially by the dotted lines in Fig. 150. This condition is to be avoided, since a prolonged application of the increased voltage V_1, V_3^x, to the potential windings is liable to overheat them. Analogous conditions arise on the reversal of a current transformer secondary, but in this case care is necessary to discriminate between want of load balance and incorrect polarity.

The direction of phase rotation of the secondary pressures and currents may conveniently be checked by a **phase rotation indicator** as described on p. 255. Failing this, the

polyphase windings of a power factor meter may be employed for the purpose. The direction of field rotation of the instrument must be known, and the test is then made by disconnecting the current terminals and short-circuiting them while the pressure is applied. Similarly the pressure winding may be disconnected and short-circuited while the current is flowing. By noting the direction of deflection due to induction the phase rotation of the current and pressure secondaries can be determined.

Only one test is required in the case of a balanced load instrument. The general effect of reversed phase rotation is to cause the instrument to indicate lag when the load is leading, and *vice versâ*. In the case of double-rotating field instruments (*i.e.*, those of the unbalanced load pattern) a reversal of phase rotation on one system only (*i.e.*, potential or current) results in the fields within the instrument rotating in opposite directions, and the pointer takes up no definite position.

It is advisable, finally, to carry out the following tests to ensure that a polyphase power factor meter is correctly connected :—

1. See that the pointer shows increased lag when the power factor is altered in this direction, and *vice versâ*.
2. Check the power factor on each line separately by disconnecting, or better by short-circuiting (see p. 324), the other current leads. The power factors on the various phases, tested in this way, will probably be nearly enough equal to one another.
3. Take check readings against a wattmeter, voltmeter, and ammeter, if these are available.

Phase Rotation Indicators.

In connection with the installation of many polyphase instruments, and particularly power factor meters and unbalanced load watt and watt-hour meters, it is essential that the various voltage and current connections should be

made in a definite way with regard to the order of phase progression. In the case of a three-phase system, for example, the various lines may be numbered 1, 2, and 3, to represent the order in which they attain their maximum voltage with reference to the neutral point. A **convention has been arrived at** in this connection **by the Engineering Standards Committee**. Fig. 151 shows the application of this convention to a three-phase unbalanced load wattmeter. The phases are either numbered 1, 2, and 3, or coloured red,

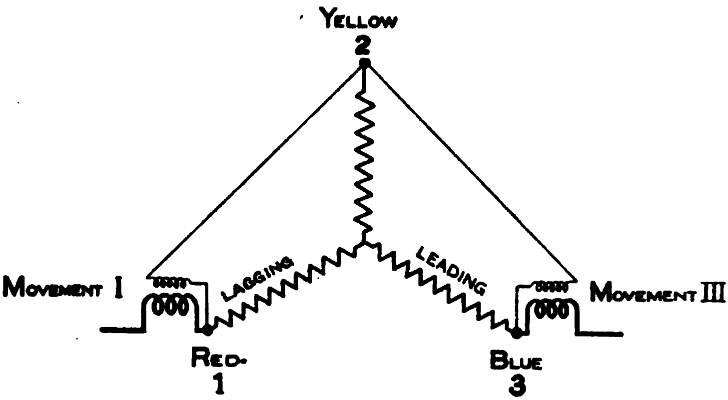


FIG. 151.—Standard Phase Rotation Diagram.

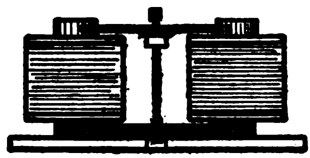
yellow, and blue, respectively. In each case the phases are assumed to "come up" in the order 1, 2, 3.

A simple means of determining the direction of phase rotation lies in connecting the supply to a small induction motor. The direction of rotation of the rotor is then an indication of the direction of phase rotation.

Fig. 152 illustrates the Everett-Edgcumbe **phase rotation indicator,** which is based upon this principle. The three leads marked 1, 2 and 3, respectively, are clipped on to the supply terminals, and the rotation of the iron disc indicates whether the phase rotation is 1, 2, 3 or 1, 3, 2. These instruments are usually provided with pressure windings, but can be arranged for working in the secondaries of current

transformers. The power taken is extremely small, say, about 0·5 volt-amperes per phase.

A **simple method of determining phase sequence** when a rotation indicator is not available has been described by T. W. Varley in the *Electrical World*.[1] If two similar incandescent lamps and a choking coil of suitable range are connected in star on a three-phase system, one of the two lamps will have a lower pressure across its terminals than the other, depending upon the direction of phase rotation. Referring to Fig. 151, if the lamps are connected from lines 1 and 3 to the artificial neutral point, and the choking coil from line 2 to the neutral point, the phase rotation will be clockwise (*i.e.*, phases come up 1, 2, 3), if the right-hand lamp is the brighter, and *vice versâ*. A condenser can be substituted for the choking coil, when one of sufficient capacity is available, and in that case the order is reversed; that is to say, a clockwise phase rotation is indicated by the left-hand lamp being the brighter.



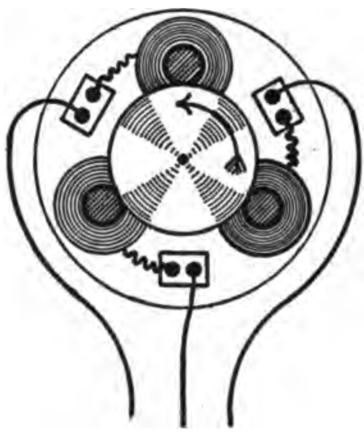


FIG. 152.—Phase Rotation Indicator.

Kapp has shown[2] that phase rotation may be determined **by means of a wattmeter** if provision is made for the switching of a condenser into the pressure circuit.

The **method of using a polyphase power factor meter**

[1] See *Electrical Review*, Vol. LXXX., p. 605 (1917).
[2] "Determination of Sequence of Phase from Wattmeter Readings," *Journal Inst. E.E.*, Vol. LV., p. 309 (1917).

for determining phase progression is dealt with on p. 255. It may be pointed out, however, that a phase rotation indicator is much more sensitive and convenient for this purpose.

Frequency Meters.

The determination of the frequency of an alternating current is a matter of some difficulty, owing to the fact that most electrical phenomena which are dependent upon frequency are also dependent upon wave form. For example, some of the earlier instruments were based upon the **variation**

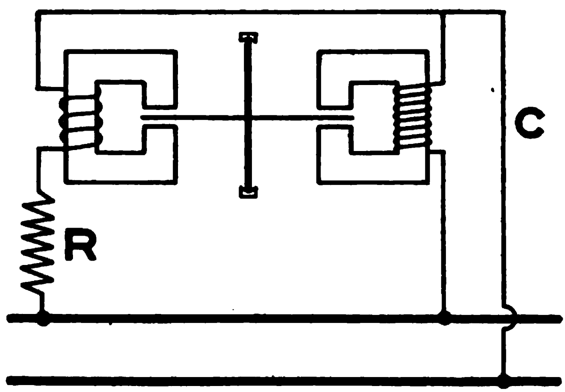


FIG. 153.—Induction Frequency Meter.

of current in a circuit containing capacity or induction with changes of frequency. They were, in fact, very similar in principle to the power factor meter shown in Fig. 140, except that the coils *nn* were wound with fine wire and connected in parallel with the *a* and *b* circuits across the mains. The ratio of the currents in *a* and *b* (and with it the reading) thus depended upon the frequency and wave form of the applied voltage.

A modification, based upon the induction principle, is illustrated in Fig. 153. Two electro-magnets similar to those of an induction voltmeter (see p. 166) act in opposite directions upon a pivoted disc which carries a pointer. Each is connected

across the mains, the one direct and the other through a non-inductive resistance, R. The windings are so proportioned that at normal frequency the two torques are equal and opposite. Should the frequency fall, the current in the right-hand element is increased, while that in the other remains unchanged, so that the disc tends to rotate in a certain direction, whereas if the frequency rises it tends to rotate in the other. No spring or weight control is used, but the disc is so shaped that as it rotates one side comes more and more into the magnet gap, while the other recedes from it, so that equilibrium may be established at all points, and each position represents a definite frequency. The scale can consequently be graduated to read direct in periods per second.

Moderate variations of pressure affect both movements equally, so that the deflection is unchanged thereby; but the effect of wave form is twofold. With a flat-topped wave there is a reduction in current, but there is also the distorting effect of the saturation of the iron (see p. 84). As a result, the readings are much affected by the wave form. This can be got over to some extent by connecting in series with both elements an inductive resistance which partially "filters out" the higher harmonics. Such an inductive resistance, common to both circuits, can be connected in the line C. The instrument, however, possesses other disadvantages, notably a considerable consumption of energy and a comparatively cramped scale.

The **ohmmeter principle** has been applied in the Weston frequency indicator. In this case an arrangement similar to the soft iron ohmmeter (Fig. 50) is used. In Fig. 154 let two coils, C_1 and C_2, fixed at right angles to one another, be connected to the centre point of two resistances, R_1 and R_2, joined across the mains. C_1 is joined through an inductive resistance to one pole, and C_2 through a non-inductive resistance to the other. For simplicity, let it be assumed that R_1 and R_2 are of sufficiently low resistance to maintain the point *p* at mid-potential under all conditions. It is then clear that the position taken up by the needle N depends upon the relative

strengths of the currents in C_1 and C_2 respectively. But this, as in the instrument previously described, depends upon the frequency, since the current in C_2 is constant, while that in C_1 is inversely proportional to the frequency. This difference in the currents can be still further increased by replacing R_2 by an inductive resistance, so that as the frequency increases, the drop across it goes up and with it the current in C_2. Such an instrument suffers from the same defects as the induction pattern, just described, as regards shortness of scale, but saturation effects do not occur, since the coils are without iron cores.

In another construction[1] the needle N is replaced by a

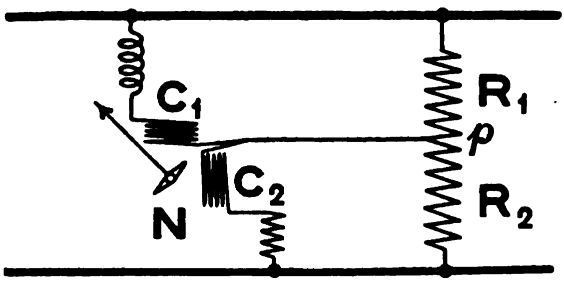


FIG. 154.—Weston Frequency Meter.

moving coil, and the two fixed windings C_1, C_2, by a four-pole iron-cored stator, giving a resultant field which changes its direction according to the frequency in much the same way as with the arrangement shown in Fig. 154, but producing a rather more open scale.

A **frequency indicator due to C. Coleman** is shown in Fig. 155 (Everett, Edgcumbe & Co.). A double universal movement similar to that shown in Fig. 79 (p. 142) is employed, one coil being connected through a choking coil and the other through a condenser, across the mains. The capacity and inductance are so chosen that at normal frequency the pointer stands at the centre of the scale. An increase of frequency causes a smaller current to flow

[1] *Elektrotechnische Zeitschrift*, Vol. 35, p. 39 (1914).

through the left-hand coil and a larger current through the right-hand, thus producing a deflection to one side. A decrease of frequency, on the other hand, causes the pointer to deflect in the opposite direction. The normal scale is extremely open, and any required spacing is readily obtainable. When still greater openness is essential a condenser and choker are connected in series with each coil, one pair being tuned to resonance at a frequency above the normal and the other pair at one below the normal. With this arrangement a slight variation in the frequency causes a large change in the current, and so gives an extremely open scale. When this open scale is not desirable the condenser is replaced by a non-inductive resistance, so that the current in one coil is independent of the frequency. Fig. 156 shows the scale of a high frequency instrument of this pattern, such as is used for wireless work.[1] The arrangement also lends itself well to the construction of graphic frequency meters (see p. 364).

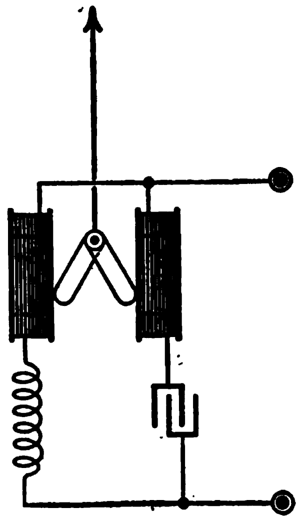


FIG. 155.—Coleman Frequency Meter.

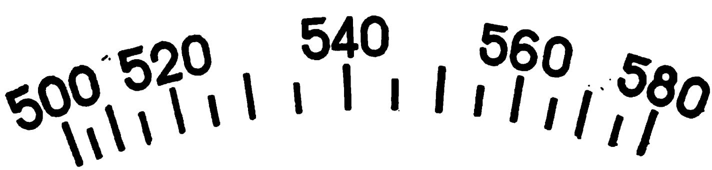


FIG. 156.—Scale of Coleman High Frequency Meter.

The indications are independent of wave form and of all ordinary changes of voltage.

[1] This refers to the power circuit of a wireless installation. For the measurement of aerial frequencies a wave meter is essential.

In another proposal[1] the variation in apparent resistance of a coil of iron wire, due to **skin effect, is made use of.** The current taken is kept constant by connecting in series with it a Nernst compensating resistance,[2] which has the property of passing an almost constant current over a wide range of pressure. The apparent resistance of the coil increases as the frequency is raised, and, the current being constant, the drop across the resistance terminals is a measure of the frequency, so that a voltmeter connected between them can be scaled direct in frequency. In practice a change of frequency from 0 to 400 cycles per second is accompanied by an increase in resistance in the ratio of 1 to 5. This arrange-

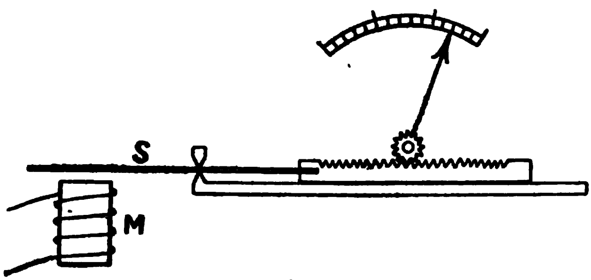


FIG. 157.—Early Resonance Frequency Meter (Campbell).

ment is equivalent to an inductive and a non-inductive resistance in parallel, and suffers from similar disadvantages.

The earliest satisfactory frequency meters were constructed on the **resonance principle** and where extreme accuracy and freedom from wave form errors is desired are still preferable to all others. The first practical application of this principle was that of Albert Campbell.[3] In this apparatus (Fig. 157) the free end of a steel spring, S, of variable length, is placed near the pole of an electro-magnet, M, energised by the current whose frequency is to be determined. If the number of complete free vibrations of

[1] *Elektrotechnische Zeitschrift*, Vol. 37, p. 45 (1916).

[2] The compensating resistance consists of a spiral of iron wire *in vacuo*. The gauge of wire is so chosen that at normal pressure it is almost red-hot, at which point its resistance increases enormously for a small increase of current, and compensation is thereby obtained.

[3] Paper read before Physical Society, *Phil. Mag.*, August, 1896.

the reed is equal to twice the frequency of the current, it will be set in resonant vibration, the cycle of operations being as follows:—As the current (and with it the flux) increases to a maximum the reed is attracted towards the pole, and springs away again as the flux falls to zero. The flux then increases in the opposite direction, and again attracts the reed, which is at that moment ready to swing towards the electro-magnet again of its own accord. The amplitude is thus gradually increased with each swing, until

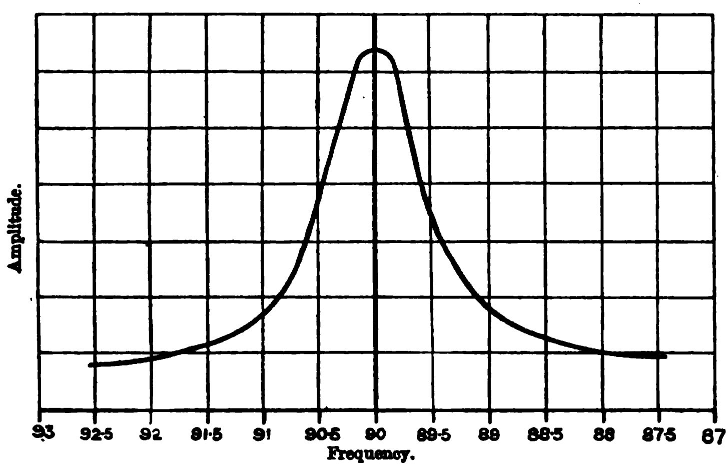


FIG. 158.—Amplitude Curve of Resonance Frequency Meter.

the energy dissipated in molecular and air friction just equals that imparted to the reed by the electro-magnet.

If the frequency of the current is slightly altered from this critical value, the impulses due to the electro-magnet will occur at unfavourable moments, sometimes too early, sometimes too late, and often at such times as to oppose the motion of the reed. As a result the very smallest alteration in the frequency is at once noticeable in the amplitude of the vibrating reed. This is very clearly seen from Fig. 158, which shows the amplitude of vibration of a reed of given length at different frequencies. It will be noticed that a change of frequency equivalent to ½ per cent. alters the amplitude by about 50 per cent.

In the Campbell instrument the length of the reed is altered by means of a rack until it is heard to be in vibration, and by gradually varying it up and down the point of maximum amplitude can be very accurately determined by ear. The frequency corresponding to this particular length is indicated by a pointer moving over a dial.

It had already been suggested by Professor Ayrton in 1889[1] that if a number of steel reeds of different lengths were held in front of an alternating current electro-magnet, the one whose free period was half that of the current would, alone, be set in vibration. R. Hartmann-Kempf in 1901 published an account of some researches on an instrument of this kind and showed that it formed an exceedingly sensitive and permanent frequency indicator.

In one form of such an instrument a number of tuned reeds are arranged round a circle, and a small electro-magnet connected to the mains is brought successively up to each. Every reed is tuned to correspond to a different frequency, and as the electro-magnet comes up to the appropriate reed it is set in strong vibration and emits a distinctive sound. The frequency to which it responds can be read on a scale fixed above it. In another variation two rows of reeds are attached, one to each side of an oblong electro-magnet. The reeds are provided with whitened ends, so that the one which happens to be vibrating can at once be detected and the frequency to which it corresponds, read off.

The frequency meter shown in Fig. 159 (that of Everett-Edgcumbe) differs from this instrument in that the reeds are arranged round a circular magnet, so that the scale is continuous and uninterrupted. In the frequency indicator due to Frahms the tuned reeds, instead of being individually attracted, as in the instruments described, are attached to a common armature which is set in vibration by the electro-magnet, and so vibrates the reeds mechanically.

A simple means of doubling the range of a frequency meter is available. It must be remembered that for every complete period the reed is twice attracted, once during each

[1] *Journal Inst. E.E.*, Vol. 18.

half-period. If a continuous current equal to the maximum value of the alternating current is superposed on it, the effect will be to neutralise one half of the alternating wave and to increase the other half, with the result that the reed only experiences one impulse per period, instead of two. In practice this may be done by providing the electro-magnet in the instrument with two windings, one carrying a continuous current and the other the alternating current. The same instrument can thus be used for two ranges, the

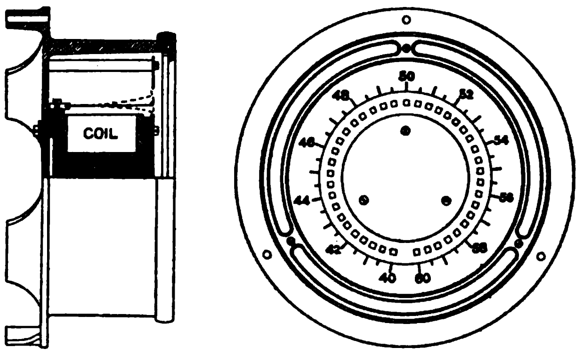


FIG. 159.—Everett-Edgcumbe Resonance Frequency Meter.

alternating winding being used by itself for the lower range and the two together for the higher.

Instead of polarising the electro-magnet by means of a continuous current winding, this can equally well be done by means of a permanent magnet, so long as steps are taken to prevent it becoming demagnetised by the alternating flux.

Fig. 160 shows a convenient method of carrying this out (Everett-Edgcumbe). Two rows of reeds are fixed to iron blocks, A, A, and are set in vibration by the electro-magnets B in the way already described (p. 264). Below the blocks are fixed two permanent horseshoe magnets, M, M, which polarise the two rows of reeds. If the ampere turns of B are so chosen that the pole strength due to the winding is approximately equal to that due to the permanent magnet, half-periods will be suppressed and doubled alternately. In this

way a reed which without the magnet M would respond, say, to 50 periods per second will, with the magnet, respond to 100 periods, and so on. This construction preserves the

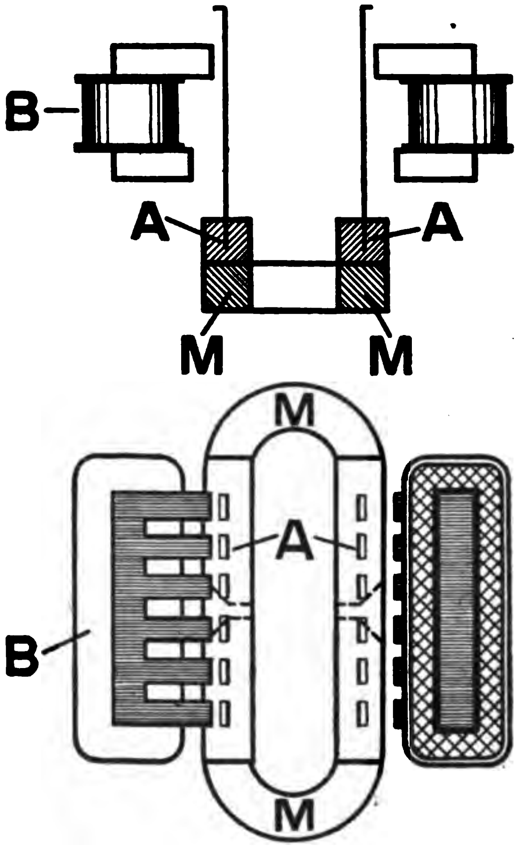


FIG. 160.—Polarised Resonance Frequency Meter.

permanent magnet from demagnetisation, owing to the distance between it and the winding.

It is to be noted that such a device is to a large extent **self-compensating, as regards the amplitude of swing,** for changes in the value of the current flowing in the coils B.

This will be clear from Fig. 161. If the winding is not polarised, the flux will alternate equally on either side of the zero line AA. If, now, a unidirectional flux, due to the permanent magnet (and equal in magnitude to the maximum value of the alternating flux), is superposed, the curve of flux will be as indicated by the shaded areas, the zero line having been transferred from AA to BB. If the amplitude of the curve is increased as shown by the dotted curve, it is evident that the areas *c*, cut off by the line BB, represent attractions experienced at the moment the reed is still swinging away from the electro-magnet. The areas *d*, on the other hand, represent augmented attractions which would increase the

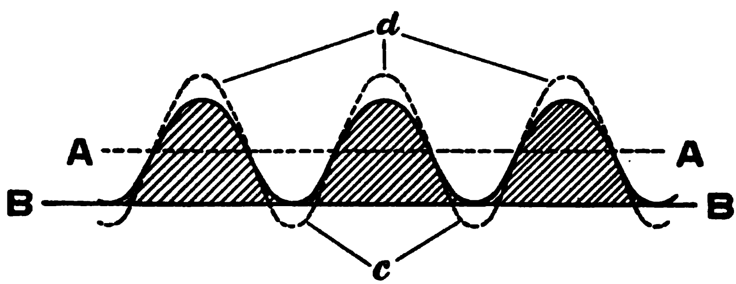


FIG. 161.—Effect of Polarising a Resonance Frequency Meter.

amplitude of swing were it not that they are nearly neutralised by the negative areas *c*. In this way, so long as the permanent magnetic flux does not exceed the maximum amplitude of the alternating flux, considerable variations in this latter will cause but little alteration in the swing of the reed.

In the case of all vibrating reed frequency meters resonance will also occur at half the frequency to which the reeds are tuned. Instead of the reed being attracted once during each complete swing, it is attracted at every alternate swing, so that the net propelling force is reduced, but definite resonance occurs. In this way, **a single instrument can be used for two ranges of frequency,** the one double the other.

Another method of obtaining two ranges by means of a

permanent magnet is shown in Fig. 162. In this instrument an oblong core, A, carrying a winding acts on the double row of reeds B, B in the usual way. M_1 and M_2 are permanent horseshoe magnets, each capable of being swung round centres at C. When in the position shown on the left (M_1), the reed B is polarised and responds to half-frequency. When swung into the alternative position, M_2 has no magnetising effect upon the reeds, and they therefore respond to the full frequency.

Permanent magnet polarised instruments are valuable for extra-high frequencies, such as are required for wireless work, since a reed tuned for, say, 200 periods can be used for 400 periods.

As pointed out when describing the Frahms instrument

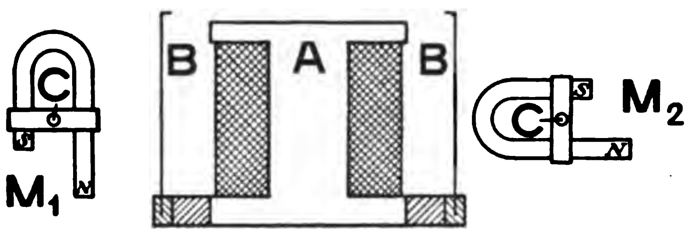


FIG. 162.—Double Range Polarised Frequency Meter.

(see also p. 369), **mechanical vibration** may set the reeds in resonant vibration, so that care is sometimes necessary to ensure that reeds, particularly when tuned to low frequencies, are not accidentally set in vibration in this way.

A difficulty which arises with **extra-high frequencies** is that, in order to keep down the free periodic time, a thick reed is essential. This entails either reduced amplitude or an increased bending of the steel, which carries with it a greater stress in the outer fibres. In fact, the stress experienced by the outer fibres of the steel, for a given displacement of the head of the reed, is proportional to—

$$\frac{\text{Thickness of reed}}{\text{Length of reed.}}$$

The maximum stress in the outer fibres to which it is safe to subject the steel depends upon its nature and the heat treatment received, but a definite value always exists, above which it is unsafe to go. On the other hand, if this maximum is not exceeded, the reeds are almost everlasting, in spite of the enormous number of repeated bends. These considerations lead in practice to an upper limit of about 300 periods per second when used direct. Above this, some form of polarisation is advisable.

In an instrument which is liable to be subjected to large **fluctuations of voltage** some provision must be made for keeping the amplitude within the limits prescribed by visibility on the one hand and durability on the other. This may be done either automatically or by hand. The simplest automatic device consists in providing the upper pole of the electro-magnet with projections between which the reeds swing, so that as the deflection increases the pull decreases. Polarisation produces a similar result (see p. 266).

Hand regulation may take the form of a multiway switch which either alters the series resistance or cuts more or less of the winding into circuit, according to the voltage. Another method is to make the relative positions of the electro-magnet and the reeds or armature adjustable, so that as the voltage rises the air-gap length can be increased.

The selection of the **intervals between neighbouring reeds** is a matter requiring some care. That shown in Fig. 159, namely half-periods, is convenient, as it enables the frequency to be determined with certainty to within say one-fifth period. There is, however, a possibility that if the frequency lay exactly between two reeds, the sensitiveness being so great (see Fig. 158), it might not be seen from a distance that any of the reeds were in vibration. Consequently intervals of a quarter-period (or say ½ per cent.) are in many cases preferable.

As has been pointed out, the exactness with which a particular frequency is picked out is very great, and with careful tuning a precision of 0·1 per cent. is easily attainable.

The use of frequency meters as speed indicators is dealt with on p. 367.

Fault and Leakage Detectors.

These instruments may be required for either of two purposes :—

(1) To indicate the existence of a fault, and possibly to determine its magnitude, or

(2) To locate it.

The indication may be required while the mains are alive, but the location is generally left until current has been cut off. The subject is a wide one, and only an outline of the methods in use for leakage detection can be given. Fault location is not dealt with in the present volume.

The **detection of a fault** or partial fault **on dead mains** is usually carried out by the Wheatstone bridge (p. 93), or by one of the ohmmeters already described (p. 103).

As shown in Fig. 46, the bridge method can be used to detect faults during working. Of late years, considerable attention has been given to the subject of leakage detection on **live mains**, largely owing to the fact that the Home Office rules for the use of electricity in coal mines recommend the installation of some form of indicator to show continuously the state of the insulation.

For **high tension**, single phase, **insulated systems** the usual method is to connect an electrostatic voltmeter (p. 183) between each main and earth. If the insulation of both mains is approximately the same, each voltmeter will indicate half the line voltage. Should one read lower than the other, it shows that the insulation of the main to which it is connected is the lower. The readings are, in fact, inversely proportional to the insulation resistances of the two mains. If the line voltage is steady, one voltmeter is sufficient, since the other voltage can always be calculated by deducting the voltmeter reading from the known line voltage. In this case it is best to connect the instrument to the main which has the lower insulation.

The value of electrostatic instruments in this connection

lies in the fact that the most minute leakage affects the potential of the system, whereas any other type of voltmeter takes an appreciable current in parallel with the leakage current and thus masks any small changes in leakage. Seeing that one pole of the voltmeter is permanently earthed, it is convenient to mount the instrument in an earthed metal case and to connect the earthed terminal to the latter. This obviates the necessity for special screening by a double case (see p. 186).

The two instruments can conveniently be combined into

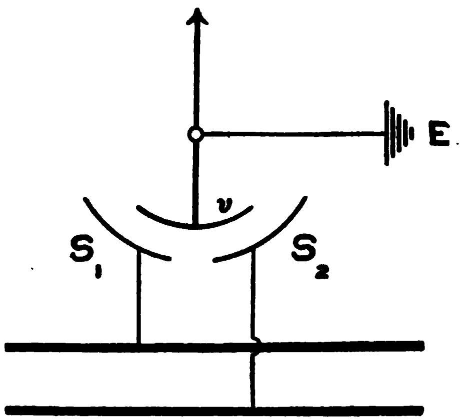


FIG. 163.—Electrostatic Leakage Detector for Two-wire System.

one, as shown diagrammatically in Fig. 163. The pivoted vane *v* is connected to earth, while the fixed sectors, S_1 and S_2, are connected, one to each main. The pointer normally stands at the centre of the scale, *v* being equally attracted by S_1 and S_2. Should the insulations be unequal, *v* will be drawn over to one side or the other, and the pointer will indicate the ratio between the two voltages, that is to say, the ratio of the insulation resistances of the two mains to one another.

A two-phase system can be treated as two separate single phase systems, so that either four distinct voltmeters or two combined instruments, similar to that shown in Fig. 163,

can be used. On a three-phase system three separate voltmeters form the best arrangement, but two combined instruments can be used if economy is necessary. Fig. 164 shows the connections in this case. Normally v_1 and v_2 have their pointers in a central position, the vanes being equally attracted by each of the fixed sectors. If main 1 goes to earth, the pressure, and with it the attraction, between v_1 and S_1 decreases, whilst that between v_1 and S_2 increases, so that the left-hand pointer moves to the left.

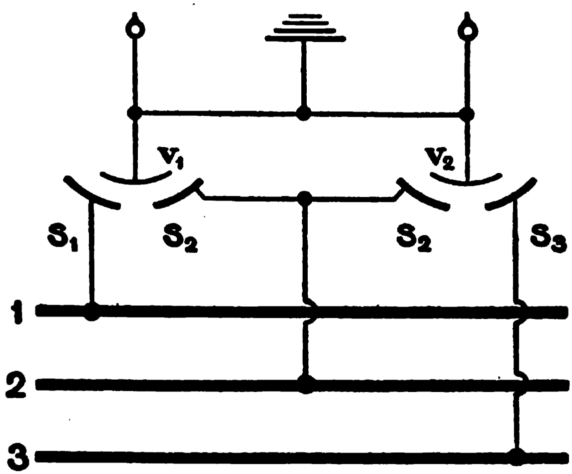


FIG. 164.—Electrostatic Leakage Detector for Three-phase System.

The right-hand pointer is unaffected, since the potentials between v_2 S_2 and v_2 S_3 are equally increased. In the same way, if line 3 goes to earth the right-hand pointer moves to the right, while the other is unaffected. If line 2 goes to earth, the attraction between v_1 and S_2 as well as that between v_2 and S_2 decreases, so that both pointers deflect inwards. It is thus possible, by means of two instruments, to determine which of the three lines is faulty.

Fig. 165 shows another arrangement, known as the "Bull's-eye" (Westinghouse). In this case the central earthed vane v is free to move in any direction and by its distance from

each of the three fixed sectors, S_1, S_2 and S_3, shows the relative pressure to earth, and consequently the relative insulations of the mains. The position of v is gauged by means of the dot seen in the centre which moves behind a fixed circle. No great precision is possible with this arrangement.

Vacuum tubes are occasionally used for a similar purpose,

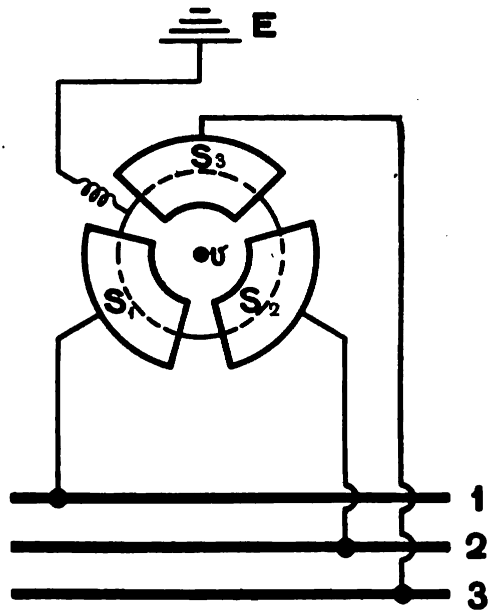


FIG. 165.—"Bull's-eye" Three-phase Leakage Detector.

and afford a rough indication, but are not nearly so satisfactory as the voltmeter methods.

It must be borne in mind, in connection with all such tests, that concordant results can only be obtained if the capacities of all lines to earth are equal. Any excess of capacity will decrease the pressure to earth of that line, although the insulation of all three may be perfect.

An advantage possessed by such methods is that the system is not put to earth. This was at one time regarded as important, owing to a supposed lessening of the danger

from shock; but with modern installations the advantage is small, and one or more transformers connected to earth with a voltmeter on the secondaries form a very useful leakage indicator. On a three-phase system a three-phase transformer can conveniently be used for the purpose. Fig. 166 shows such an arrangement. The voltmeter VM, across the open delta secondary, normally stands at zero, a deflection showing that a fault has occurred on one main. The lamps L serve to indicate on which phase it is, or the lamps can with advantage be replaced by three voltmeters.

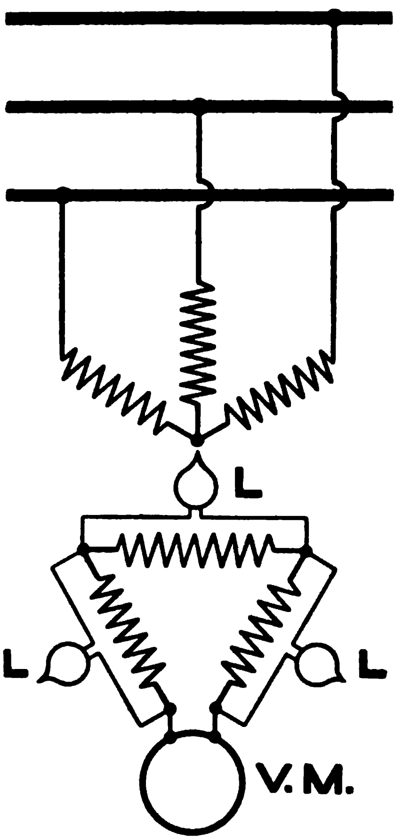


FIG. 166.—Three-phase Leakage Indicator. Transformer Pattern.

For **low tension insulated systems,** whether direct or alternating current, the same arrangements are applicable, but the choice of methods is wider.[1] For two-wire systems a voltmeter connected as shown in Fig. 167 can be used. A resistance, *rr*, is joined across the mains, and from its middle point the voltmeter VM is connected to earth at E. If the insulations of the two mains are equal, no deflection is produced, but if they are unequal, a current flows through the

[1] For a discussion of a number of tests an article by G. M. Stebbings in *Electrical Review,* Vol. 80, p. 620 (1917), may be consulted.

voltmeter. On direct current systems a central zero moving coil voltmeter can be used, and it will be deflected to one side or the other according to the insulation.

Besides the continuous indication of *relative* insulation, such a voltmeter, connected first to one main and then to the other, can be used to determine the *actual* insulation of each. The working pressure between lines (V) is first measured, and the voltmeter (of resistance r) connected successively between each main and earth, readings v_1 and v_2 being so obtained. The insulations of the two mains are then—

$$R_1 = \frac{r\ (V - v_1 - v_2)}{v_2};$$

$$R_2 = \frac{r\ (V - v_1 - v_2)}{v_1}.$$

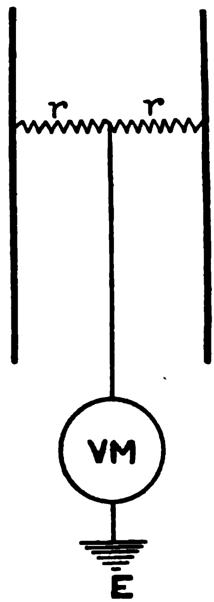


Fig. 167.—Low Tension Two-wire Leakage Indicator.

For direct current circuits, in order to save calculation, tables are often worked out from which the values of R_1 and R_2 can be read off, as also the leakage current flowing from main to main through the earth. This latter is frequently of importance. It is stipulated, for example, in the Coal Mines Regulations that it shall not exceed one-thousandth of the full-load current.

While in the case of direct current installations the method gives extremely accurate results, with alternating currents capacity effects disturb the readings to such an extent that they can only be regarded as relative.[1]

On **earthed systems** (*e.g.*, three-wire with earthed middle wire or three-phase with earthed neutral point) the methods so far given, depending as they do upon a varying potential

[1] Dr. J. Sahulka in the *Elektrotechnische Zeitschrift* describes an elaborate method of eliminating capacity effects, but it is hardly likely to be largely used in practice. See abstract in the *Electrician*, Vol. 59, p. 999 (1907).

difference between mains and earth, are inapplicable. Moreover, no thoroughly satisfactory method of continuous indication for such systems has been devised. The most usual consists in connecting an ammeter in the earth circuit, that is to say, between the earth-plate and the system. If the insulation is perfect, no current will flow, but if any main develops an earth, the leakage current will flow through the ammeter. On direct current systems the direction of the current indicates on which of the two mains the fault has occurred. On alternating current systems this can only be determined by putting an artificial leak to earth on one of the lines and noting whether the deflection on the ammeter is increased or decreased by so doing.

In order to detect slight faults, the ammeter should be a low-reading one, say, up to 1 or 5 amperes,[1] and consequently some means must be adopted for protecting it from the heavy current which flows in the case of a dead earth. A usual arrangement consists in an automatic switch which short-circuits the instrument so soon as the current exceeds a safe value. An alternative arrangement is to provide a resistance sufficient to cut down the current to a safe value even in the event of a dead earth, which resistance is automatically cut into circuit by a switch on the occurrence of a fault.

It is now, however, becoming more and more usual, particularly on three-phase systems, to insert a permanent earthing resistance in the neutral wire of such a value that the current is limited to an amount sufficient to bring out the breaker on the feeder of largest capacity. Even this reduction in current is not, as a rule, enough to protect the low-reading ammeter from damage, so that the automatic short-circuiting switch is still required. It is, moreover, essential that this switch should be extremely quick in its action, or the ammeter may be damaged before sufficient time has elapsed for the switch to close and protect it.

[1] An ammeter scaled to 1 per cent. of the current required to open the largest breaker on the system controlled will be found satisfactory.

It should be remembered that the ammeter only carries the *difference* between the leakage currents, and consequently a decreasing deflection may mean either that one main is improving or that another is getting worse. Moreover, a fault on the middle wire of a three-wire system will shunt the ammeter and thus actually decrease its readings. This may mean an increase or decrease in the current according to the relative resistance of earth and neutral feeder to the fault. At the same time these instruments have proved

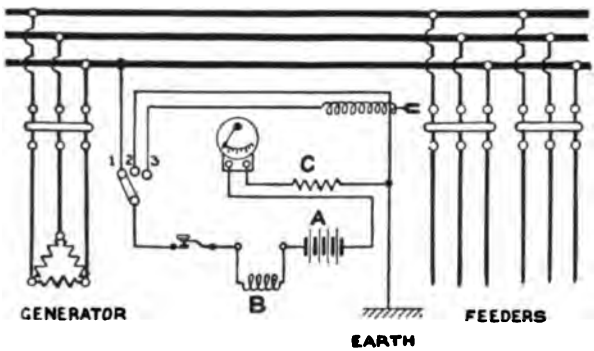


FIG. 168.—Superposed Continuous Current Leakage Indicator.

most valuable in practice, and should always be installed on earth systems.

The most accurate method is **temporarily to open the earth circuit**, if it is permissible, and then to treat the system as an insulated one. If this is done, the insulations can be readily determined, as for a two-wire system. For example, the combined insulation resistance of a three-wire system can be obtained by taking voltmeter readings (v_1 and v_3) between each of the outers and earth. Then, if V is the voltage across the outers, and r the resistance of the voltmeter, the insulation resistance of the system is—

$$R = r\left(\frac{V}{v_1 + v_3} - 1\right),$$

where $$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}.$$

In the case of an alternating current insulated system, either single or polyphase, a **continuous current method** can be used, a convenient arrangement being shown in Fig. 168. The battery A has one pole earthed through a moving coil milli-ammeter, and the other pole connected through contact 1 of the three-way switch to the bus-bars. The parallel insulation of the system is then—

$$\text{Insulation in thousands of ohms} = \frac{\text{Battery volts}}{\text{Milliamperes}}.$$

In order to protect the milli-ammeter from damage in the event of a dead earth, a high resistance is connected in series, as shown at C. The value of this resistance must be deducted from the figure given above, to arrive at the insulation of the network.

When the three-way switch is on contact 2, this resistance alone is in circuit, and the milli-ammeter can then be used to measure the voltage of the battery, which must be known for the calculation of the insulation resistance. Attached to contact 3 of the switch is a flexible connection which can be joined on to any disused feeder so as to determine its individual insulation. The choking coil B prevents the milli-ammeter from being damaged by a flow of alternating current.

In place of the moving coil milli-ammeter, which is usually scaled in ohms on the assumption of a constant voltage, a direct-reading ohmmeter can be used to advantage (see p. 103). As such an instrument is independent of changes of voltage, a magneto-generator may be used instead of a battery.

Special Fault-testing Ammeters have been designed for the purpose of measuring the current in mains without the necessity of breaking the circuit. For alternating current the split core transformer is available (see p. 328), whilst for continuous current a portable moving coil ammeter with removable magnet has been devised. In this instrument the moving coil is energised by means of a self-contained dry cell, and the usual permanent magnet is replaced by a

soft iron magnet which projects through the back of the case. This magnet can be removed and slipped over the cable to be tested and then replaced in position, so that the current flowing in the cable energises the magnet and, if the current flowing through the moving coil is constant, the deflection will be proportional to the magnetic flux. A number of precautions are necessary in using such an ammeter, and in particular it is essential that the magnet should always be magnetised in the same direction and be removed and replaced each time a reading is required, so that the flux may in each case be brought up to its full value from zero.

Synchronising Devices.

The simplest form of synchroniser consists of an **incandescent lamp** joined across the contacts of a single pole

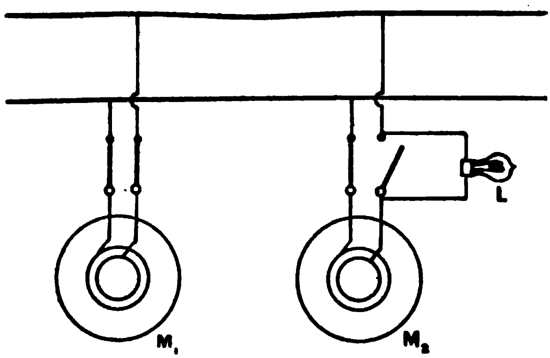


FIG. 169.—Simple Synchronising Lamp.

switch connecting the two machines to be paralleled. This arrangement is shown in Fig. 169, where L shows the lamp in question, and M_1 and M_2 are the two generators to be paralleled. If they are running at different speeds, the phase of the terminal voltages is continually changing. When in phase the pressure across the lamp terminals will be zero, while when out of phase it will be twice that of each generator. As a result the lamp will go through a complete cycle of illumination for each period gained by one

alternator over the other. The rapidity of the "flicker," therefore, gives an indication of the extent of the difference in speed, and complete extinction shows that the correct moment for closing the switch has arrived.

Owing to the indefiniteness of such an indicator, an improvement was introduced in the shape of a **synchronising transformer,** shown in Fig. 170. This consists of a transformer, T, having a double primary and a single secondary, which feeds the synchronising lamp. The windings are so connected that when the generator M_2 is "in phase" with the bus-bars the lamp is fully alight. It is, then, considerably

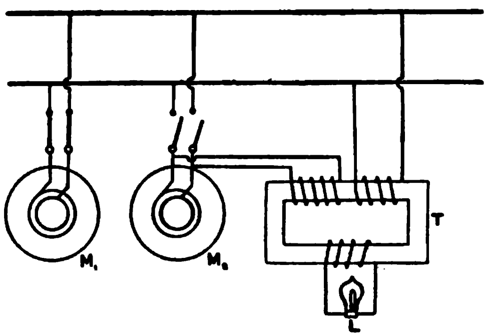


FIG. 170.—Synchronising Lamp and Double-wound Transformer.

easier to determine the correct moment for switching in than when synchronism is indicated by the lamp being out, as is necessarily the case with the connections shown in Fig. 169. Moreover, when using the transformer it is unnecessary to close one pole of the switch before the other.

In place of the lamp a dead-beat voltmeter is often provided, and is easier to use. In the case of the transformer (T, Fig. 170), assuming that the ratio of primary to secondary turns is $1 : n$, and that there is no magnetic leakage, the secondary voltage, as measured by the voltmeter, will vary between zero and $2n$ times the primary voltage, according to the phase relation existing between the generator and the bus-bars. The correct moment for

switching in will be when the voltmeter needle reaches its maximum deflection.

A little consideration will show that when the generator and bus-bars are 180° out of phase with one another the resultant flux is *nil*, assuming no magnetic leakage ; that is to say, a condition has been reached which is equivalent to an infinitely large secondary load on an ordinary transformer. As a result either the transformer will be burnt out or its fuses blown. To make such an arrangement practicable, therefore, both the magnetic leakage and the number of primary turns must be increased to such an

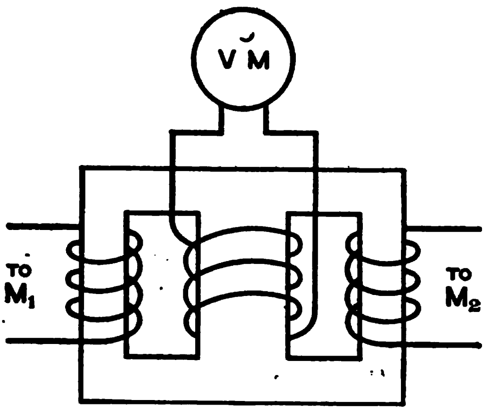


FIG. 171.—Synchronising Transformer.

extent as to provide sufficient self-induction to reduce to a reasonable amount the current which flows when the machines are out of phase. This is found in practice to entail so large a transformer that its cost is quite as high as that of two separate transformers each with a single primary and secondary, and which are therefore to be preferred.

An improved form of synchronising transformer is shown in Fig. 171. Each of the outer limbs has a winding connected to one of the generators M_1 and M_2, while that of the middle limb is connected to a voltmeter, VM. The action of the

transformer will be clear from the illustration, and it will be seen to be free from the defects just enumerated.

In the case of the transformer shown in Fig. 170 and to a somewhat smaller extent that in Fig. 171 also, when the winding connected to M_1 is alive the generator M_2 will be made alive, owing to the two windings acting as primary and secondary respectively. Unless, therefore, care is taken to open the synchronising transformer circuit whenever the generator to which it is connected is shut down, there is considerable danger to life. In modern practice, moreover, high tension synchronising bars, which such a system requires, are seldom installed, and each generator is usually provided with its own transformer, which may often work a voltmeter or wattmeter as well. The secondaries of these transformers are so arranged that for synchronising purposes any two can be temporarily connected in series to the terminals of the synchronising voltmeter by means of a plug or switch.

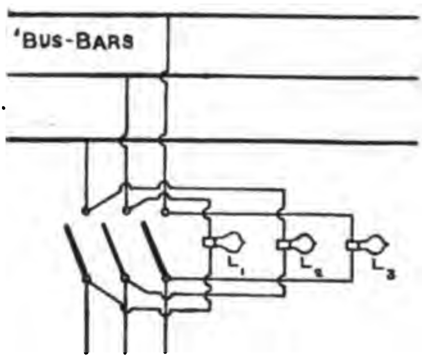


FIG. 172.—Three-lamp Synchroniser.

On **polyphase circuits** it is possible so to arrange the synchronising lamps that they show whether the speed of the incoming generator is too high or too low. Fig. 172 shows the connections of such an apparatus. L_3 is joined up as an ordinary synchronising lamp, and serves as such, synchronism being indicated by its remaining dark. The lamps L_1 and L_2 are cross-connected, as shown. Assuming the generator to be exactly in phase with the bus-bars and the switch to be open, the phase displacement between the potentials at the terminals of L_1 will be 120°, and similarly for L_2. If now the frequency of the generator be slightly increased,

the potentials applied to the terminals of one of these lamps will be brought more into phase and those applied to the other less. Lamp L_2, for example, will become gradually brighter, while L_1 grows less bright. Thus the light appears to have travelled from L_1 to L_2. A little later on it will have travelled to L_3, and then back to L_1, and so on. If, on the other hand, the frequency of the generator had decreased, the apparent rotation would have been in the opposite direction. Consequently L_3 acts as a synchronising lamp, while the three together show whether the speed of the incoming machine is too high or too low. A disadvantage possessed by this arrangement for high tension work is that three transformers are required for each generator, besides which, in common with all lamp synchronisers, it labours under the disadvantage of being insensitive.

A vibrating reed frequency indicator (see p. 262) can be used as a synchroniser, and has been adopted to some small extent. As usually constructed, such an instrument consists of three distinct groups of reeds mounted in a single case. Two of these serve to indicate the frequencies of the bus-bars and incoming machine, respectively, while the third has two windings, one connected in series with each of the other reed groups. Consequently the flux in the case of this latter set of reeds fluctuates between zero and a maximum for each cycle lost or gained by the incoming machine. Whenever the latter is in phase with the bus-bars, the amplitude of swing is a maximum. By watching the surge of these reeds it is possible to determine with fair accuracy the correct moment for switching in.

All such synchronising devices are rapidly giving place to "**rotary synchronisers**," "synchroscopes," or "synchronoscopes," as they are variously called. These instruments are in reality special forms of phase meter in which the pointers are free to revolve, and in which no scale is provided, only the point corresponding to coincidence of phase (*i.e.*, synchronism) being required.

If in the case of the power factor indicator shown in

Fig. 140 the coils *nn* are wound with fine wire and connected to the terminals of one alternator, whilst the windings marked

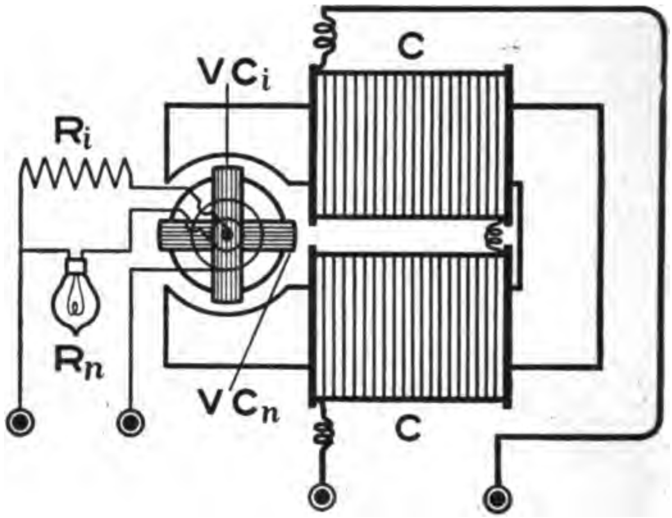


FIG. 173.—Lincoln Synchroniser.

a and *b* are connected to another, supposed to be giving the same frequency, then the pointer will indicate the phase relationship of their E.M.F.'s. If, on the other hand, there is a slight difference of frequency, this phase relationship will be continually changing, and the pointer will revolve at a speed dependent upon the difference. It will, in fact, make one revolution for each complete cycle gained by one generator over the other. The direction of rotation, moreover, will depend on which of the two is running at the higher speed.

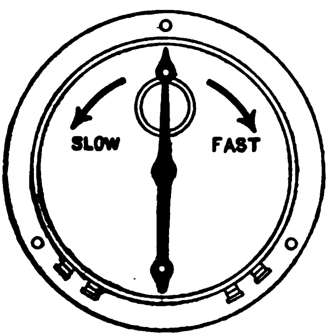


FIG. 174.—Everett-Edgcumbe Rotary Synchroniser.

The synchroniser devised by Lincoln works on this prin-

ciple. The coils CC (Fig. 173) are wound on a laminated iron horseshoe magnet, and the moving coils VC_i and VC_n are mounted on a laminated armature attached to a spindle running in ball bearings and carrying the pointer. The resistance R_n consists of an incandescent lamp, and R_i of a choking coil.

One pattern of Everett-Edgcumbe rotary synchroniser is shown in Fig. 174, and the connections in Fig. 175. The rotor carries a two-phase winding, one pair of coils being connected in series with a non-inductive resistance (R_n, Fig. 175), whilst the other pair is connected in series with

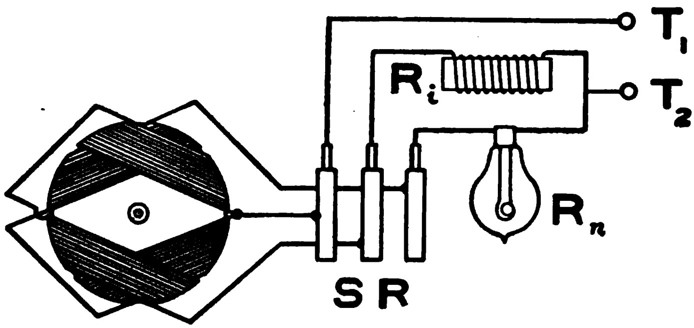


FIG. 175.—Internal Connections of Synchroniser shown in Fig. 174.

a choking coil (R_i), and the two circuits joined in parallel across the terminals of one of the alternators. By this means the current in R_i is made to lag some 85° behind that in R_n, and a fairly uniform rotary field is produced. In the earlier forms of instrument the stator carried a similar two-phase winding on a circular laminated core which surrounded the rotor. In the later patterns, however, a single phase stator is employed consisting of four coils on a four-pole core. These windings are joined in series in such a way as to give alternate north and south poles, and are connected to the incoming generator either directly or through a transformer. The rotor connections are shown in Fig. 175, one pair being connected through the left-hand slip-ring to the terminal T_1, and the other end through the right-hand

slip-ring and lamp R_n to the terminal T_2. The other windings are similarly connected to T_1 and through the choking coil R_i to T_2. The rotor is connected to the bus-bars by means of the terminals T_1 and T_2, whilst the stator is joined, as has been said, to the incoming generator. Since the rotor makes a complete revolution for each two cycles lost or gained, a double-ended pointer is attached to the spindle, and is so set that when standing vertically, as shown in Fig. 174, the machines are exactly in phase.

Provided the engine-driver is sufficiently near the instrument to be able to see the pointer, he can at once tell whether

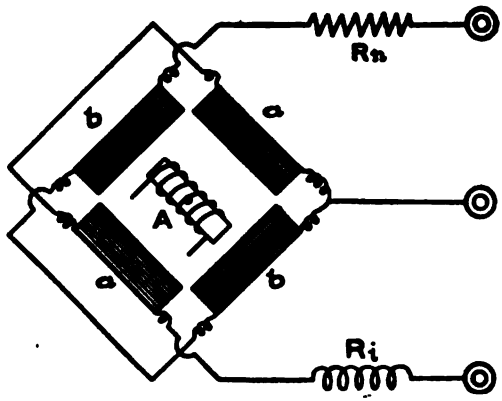


FIG. 176.—Connections of Synchroniser shown in Fig. 177.

his generator is running too fast or too slow, and whether by much or little. In large engine rooms, however, this is seldom possible, and a signalling arrangement has consequently been provided, which consists of a red and green light respectively, which is shown in the small round opening in the upper part of the dial (Fig. 174), according as the speed is too high or too low. On the rotor spindle is carried a toothed disc, which engages with one or other of two pawls according to its direction of rotation. These pawls are attached to a vertical arm, pivoted at its lower extremity, which when the pawls engage is tilted over in one direction or the other. This arm carries two transparent coloured screens side by side

and so arranged that when at one end of its travel a green screen is opposite the opening in the dial and is illuminated by the lamp inside the instrument, but so soon as the rotor reverses the red screen takes its place.

In another modification all the windings are fixed and slip-rings are dispensed with. The working principle of this instrument is shown in Fig. 176. The coils *aa* are connected in series with an inductive resistance, R_i, and the coils *bb* with a non-inductive resistance, R_n, so as to produce a two-phase rotary field. Within these coils is pivoted a soft iron "needle," A, carrying a winding energised from one generator, while the four coils are connected to the other generator. It will be seen that such an arrangement is equivalent to that of the power factor indicator shown in Fig. 140 and acts as a synchroniser in the way already described.

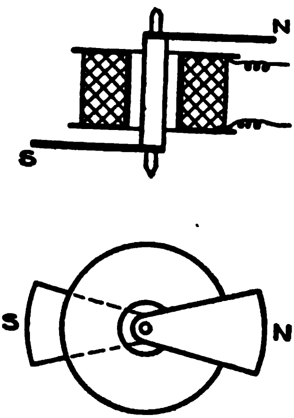


FIG. 177.—Fixed Winding Synchroniser.

In order to obviate the use of slip-rings to lead the current into the central coil A, the latter is constructed as shown in Fig. 177. The Z-shaped rotating iron needle S and N is surrounded by a winding which induces north and south poles in such a way that the moving system becomes equivalent to the bar magnet A (Fig. 176), and with the advantage that the winding can be fixed and rubbing contacts avoided.

The behaviour of the instrument is identical with that shown in Fig. 174, except that, the stator having a two-pole winding instead of a four-pole, the pointer is single-ended and makes one complete revolution for the gain or loss of each cycle instead of making only half a revolution, as in the case of the instrument previously described.

Another form of synchroniser allied to the rotary pattern is that of Weston. The connections are given in Fig. 178.

The movement consists of a wattmeter having its fixed and moving coils wound with fine wire. The one is connected through a resistance, R, and terminals, BB, to the bus-bars, and the other through a condenser, C, and terminals, G, to the incoming generator. In order to simplify matters, let it be assumed that the incoming machine is running at the same frequency as and in phase with the bus-bars. Then the

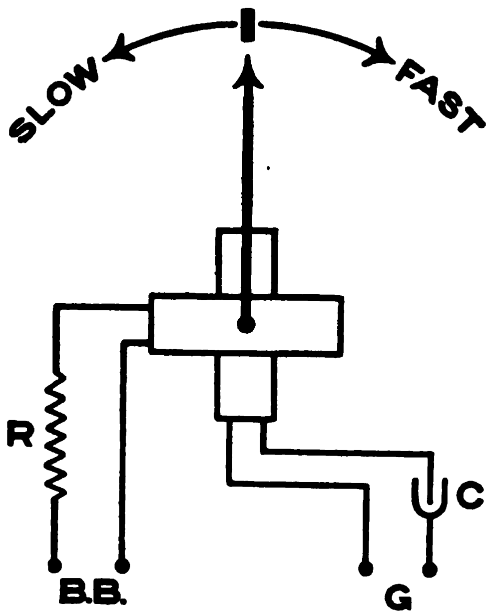


FIG. 178.—Weston Synchroniser.

wattmeter movement will have currents in its two coils which are 90° out of phase with one another, since one of them is connected in series with a condenser. Consequently the torque is *nil*, and the pointer (which is slightly "bottom-heavy" remains at the zero point in the centre of the scale, as shown in Fig. 178. If now, while still running at constant frequency, the incoming machine drops back slightly in phase, the pointer will be deflected in one direction (say to the left), and if it gains in phase, the deflection will be in the other direction (to the right). It is thus

evident that if the incoming machine drops back in phase through a whole period, the pointer will begin by a deflection to the left during the first quarter-period, and at the end of a further quarter-period it will have returned to zero in the centre of the scale. The next quarter-period will show a deflection to the right followed by a return to zero once more.

It will be seen that the pointer passes the central mark at the instants both of exact synchronism and of exact opposition, so that, in order to make it useful as a synchroniser, some means must be found to distinguish one passage across the dial from the other. This is done by placing the pointer behind a scale of opal glass, which is illuminated from behind by a synchronising lamp (see p. 279). Such a lamp only glows when the generator is nearly in phase with the bus-bars, so that the travel of the pointer across the dial in one direction is seen by its shadow on the opal scale, while its travel back is invisible. A little thought will show, moreover, that the direction of visible travel indicates whether the incoming generator is running too fast or too slow in accordance with the lettering seen on the scale.

This synchroniser, therefore, performs the same functions as those of the rotary pattern already described, but is not so convenient to use owing to the fact that the pointer is only visible through part of a period, instead of being continuously in view, so that greater skill and judgment are demanded of the operator.

In conjunction with the increasing use of remote control switching arrangements, **automatic synchronisers** have been employed to some small extent, but whether they will be largely taken up in the future seems doubtful. These synchronisers consist essentially of three parts, corresponding to the three factors determining correct synchronism, namely, equality of voltage, frequency and phase. The apparatus, therefore, comprises a voltage relay and a phase relay connected in series, which, provided they have simultaneously closed a circuit for a sufficient length of time, actuate an automatic switch which throws the incoming

generator on to the bus-bars. It is essential that a time element should be introduced, as otherwise it would be possible for the machine to be switched in when momentarily in phase, although running at much too high or too low a speed. The paralleling of a modern alternator with a rotary synchroniser is such a simple matter that the great complication and delicacy of the automatic synchroniser do not seem to be warranted.

Pyrometers.

The electrical pyrometer stands alone as a rapid and accurate means of measuring temperatures which lie beyond the range of the ordinary mercury thermometer. The simplicity of the method is so great that in its cruder forms it can safely be placed in the hands of any intelligent workman, whilst, with the addition of various refinements, it is by far the most accurate and flexible thermometer known.

These instruments may be divided broadly into two classes :—

(1) Those in which the thermometer is subjected to the temperature to be measured (resistance and thermo-electric pyrometers).

(2) Those in which radiation from the glowing body is concentrated upon it by means of a lens or mirror (radiation and optical pyrometers).

Resistance Pyrometers.

The earliest resistance pyrometer was that constructed by Sir William Siemens, in the first instance for deep sea measurements and later for high temperature work. In the **Siemens pyrometer** a differential galvanometer was so connected that one of its coils was in series with a platinum spiral exposed to the temperature to be measured, while the other was in series with an adjustable resistance. The value of this resistance, which gave a balance when the platinum spiral was cold (R_1), and also after the thermometer coil had attained the temperature to be measured (R_2), was noted.

The difference, R_1—R_2, was then a measure of the rise of temperature.

In place of the differential galvanometer the direct-reading **Wheatstone bridge** (see p. 93) is often used. Fig. 179 shows a convenient arrangement. The platinum working coil PC, enclosed in a porcelain protecting tube (see p. 294), is exposed to the temperature to be measured. The ratio coils R_1 and R_2 are of equal resistance, and a compensating resistance, CR, is so adjusted, once for all, that when the platinum coil is at a temperature of 0° C. the point of contact for no deflection on the galvanometer is at the zero point of the slide-wire SW; that is to say, since

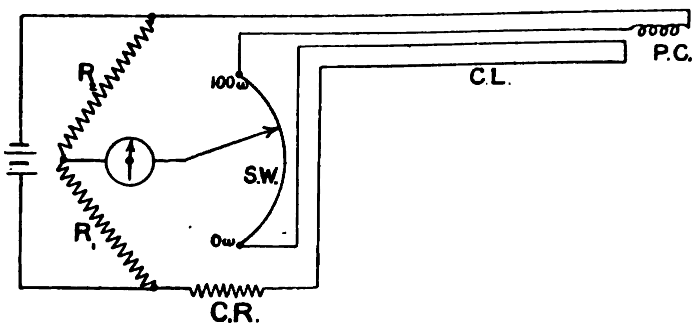


FIG. 179.—Resistance Pyrometer Connections.

R_1 and R_2 are equal, the two circuits containing PC and CR respectively are equal in resistance. If now the temperature of the coil PC is raised to, say, 100° C., the equilibrium will be upset, and a new point of balance will be obtained. Such a point can be found for all temperatures up to the limit of the slide-wire, which in Fig. 179 is supposed to have a resistance of 100 ohms. As the contact is moved from the point marked 0 ω along the slide-wire, resistance is gradually removed from the PC circuit and inserted in the CR circuit, and since these two circuits must always remain of equal resistance (R_1 and R_2 being equal), it follows that the number of ohms thus transferred from one circuit to the other by moving the contact must be exactly equal

to the increase in resistance of PC due to its rise of temperature. The corresponding temperature can either be obtained from a table, or the slide-wire itself can be graduated direct in degrees.

Since for many purposes it is essential to place the thermometer coil at some distance from the bridge, the resistance of the copper connecting leads, which varies with the surrounding temperature, may form a considerable proportion of the whole and consequently affect the readings. Moreover, for the same reason, the depth to which the thermometer was inserted in the furnace would introduce errors. Both can, however, be avoided by running two compensating leads, CL, of the same material as, and by the side of, the connecting leads. The change in resistance of both pairs being approximately the same, the reading will be unaffected (see also p. 297 as regards self-heating).

Very careful determinations have been made by Callendar and other observers of the **relation between temperature and resistance in the case of platinum,** which is the material generally used. For small changes it is usually assumed that the resistance of a metal is directly proportional to its temperature. Over the wide range required in thermometry, however, this assumption cannot be made. According to Callendar, a correction, t, must be added to the "platinum temperature,"[1] as it is often called, to arrive at the true temperature.

Up to 1,000° C. it is found that—

$$t = k\left(\frac{T^2}{10,000} - \frac{T}{100}\right) = k\left(\frac{T}{100} - 1\right)\frac{T}{100},$$

where T is the true temperature, and k is a constant depending on the chemical composition of the wire. For pure platinum $k = 1{\cdot}5$. In applying the formula to an observed temperature (*i.e.*, platinum temperature), T is unknown, but the observed platinum value can be employed instead of T on the right-hand side, and the value for T so found

[1] The "platinum temperature" is that obtained by assuming that the temperature resistance curve is a straight line passing through the 0° and 100° points.

can be used for a second calculation of *t*, and so on, until the correction is negligible. In practice either a table of corrections is used, or the bridge can be graduated direct in true degrees. A thermometer graduated in platinum temperatures, and correct at 0° and 100° C., will read about 7 per cent. low at 500° C. and nearly 20 per cent. low at 1,000° C.

If several thermometers are to be used with the same bridge, it is essential that they should all comply with the following conditions:—(1) The resistance of PC (Fig. 179) must be so chosen that the increase in resistance between 0° and 100° C. (the "**fundamental interval,**" as it is often called) is the same in all cases, and (2) the resistance of the thermometer circuit added to that of the slide-wire must be equal at 0° C. to CR+CL. The second requirement can be fulfilled either by making up the resistance of the thermometer to a given value, by means of a swamping resistance of negligible temperature coefficient, or by giving CR a different value for each thermometer. The fundamental interval has usually a value of 1 ohm or, more rarely, of 10 or 20 ohms, and the resistance at 0° C. lies commonly between 3 and 60 ohms. A further question of importance is the heating of the active coil by the testing current. This is dealt with more fully on p. 297.

The arrangements so far described are zero methods in which it is necessary to make an adjustment until the galvanometer pointer is brought back to zero.

In Fig. 179, if the slide-wire contact is left in a fixed position any change in the resistance of PC due to a change of temperature will be accompanied by a **deflection of the galvanometer**. The greater the change of resistance the larger will be the deflection, so that with constant battery pressure the galvanometer can be provided with a scale marked with temperatures. The same remarks apply to the differential arrangement of Siemens. In both cases any variation in the voltage of the battery can be allowed for by providing a standard resistance to take the place of the platinum coil, and when this standard is in circuit the pointer

should come to a definite point on the scale, usually indicated by a red mark. If it does not, it is brought there by means of a variable magnetic shunt whereby the sensibility of the instrument can be changed as required. In the case of the Wheatstone bridge arrangement (Fig. 179) the effect of voltage variations can be minimised by so proportioning the resistances that the galvanometer carries no current at the mean temperature to be measured.

Another alternative is to employ one of the **ohmmeter** devices described on p. 103. With such instruments the indications can be made quite independent of the applied voltage so that, if need be, they can be connected to the supply mains, although owing to insulation troubles this is not advisable. A number of ranges can be given with a single indicator, as explained when describing the ohmmeter.

The **metal generally used for the thermometer proper** is platinum, and for high temperatures no other should be employed. For low temperatures nickel or copper are often used, both on the score of price and as having higher temperature coefficients. It has been shown by Northrup[1] that molten copper increases uniformly in resistance with rise of temperature, so that a possibility exists of the construction of a pyrometer on these lines for temperatures exceeding 1,100° C. (copper melting at 1,084° C.).

The **mounting of the wire** necessarily depends both upon the temperature to be dealt with and the conditions of use. For atmospheric temperatures enamelled wire wound on an open frame can be used, and takes up changes rapidly. For higher temperatures some form of **protection** is essential, and the table below enumerates the materials more commonly used, together with the temperatures up to which they are available. No hard and fast rule can be laid down in this latter respect, as so much depends upon the conditions of use, that is to say upon whether subjected to corrosive gases, to rapidly varying changes of temperature, how supported, length of exposure, and so forth.

[1] *Journal of Franklin Institute,* 1914.

Material.	Temperature up to which available.
Glass	400° C.
Copper	600° ,,
Steel	800° ,,
Silica	1,000° ,,
Porcelain	1,200° ,,
Molybdenum	1,200° ,,
Alundum (aluminium oxide) . .	1,400° ,,
Fireclay	1,400° ,,

Silica has the great advantage of having a negligible coefficient of expansion with heat, so that it is not liable to crack, as is porcelain, if suddenly heated or cooled. The tubes, whether of silica, porcelain, etc., are usually protected by an outer sheath of steel or iron, which can be replaced when burnt through. Alundum is too readily permeable by gases to be satisfactory. Molybdenum is usually employed in the form of a cap at the end of a nickel tube, and is useful for taking temperatures in molten brass. Whatever material is used, if the tube is horizontal it should be supported throughout its length, and, except in the case of metals and of silica, should not be subjected to sudden changes of temperature.

The mounting of the active coil itself requires care, since platinum in contact with fireclay or porcelain at high temperatures is rapidly contaminated and increases considerably in resistance. It is usual, therefore, to mount the platinum spiral on mica, due provision being made for expansion, and to weld this on to two thicker connecting wires. Two compensating leads, short-circuited at their lower ends (CL., Fig. 179), also pass down the tube, being kept apart by mica or silica separators. It should be added that, whatever precautions are taken, the use of the platinum resistance pyrometer is restricted to temperatures of less than 1,000° C., since above this platinum becomes appreciably volatile.

Fig. 180 shows a **typical resistance thermometer.** The

platinum spiral B is protected by an inner porcelain tube, C, cemented into the metal body D, carrying a porcelain block, A, on which are mounted the four terminals. A removable steel sheath, E, held in place by the flange F, protects the porcelain tube from damage. The four leads which pass down the tube (two main and two compensating) are separated from one another by pierced mica discs, G. The terminals are enclosed and protected from fumes, etc., by the metal cap H, to the apex of which is fixed the end of the flexible protecting sheath K, enclosing the external leads.

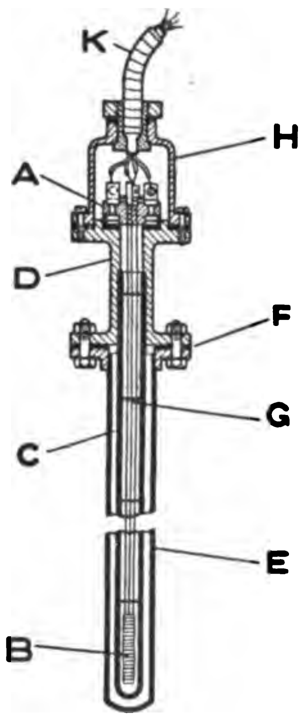


FIG. 180.—Typical Resistance Thermometer.

A pyrometer of this description is suitable for measurements up to 1,000° C. for short periods, but above 700° C. the steel sheath should be removed, and care is then necessary to avoid breaking the porcelain tube either by a blow or by too rapid heating. For continuous use 600° C. should not be exceeded. Various other constructions of straight and bent porcelain enclosed pyrometers have been devised for particular purposes, but that illustrated in Fig. 180 is typical of the majority.

Fig. 181 shows a very satisfactory arrangement which consists in mounting the platinum spiral in a tube of transparent silica. The spiral A is closely wound on a hollow rod of silica, C, and is attached at each end to a platinum band, B, connected to the leads DD, which are kept apart by means of a fine silica tube, E, threaded on to one of them. The whole is next pushed into the outer silica sheath F, which has one end closed, and this is shrunk on to

the winding by a special process, so that the whole is fused together. In this way the winding is entirely embedded in the silica, which protects it from damage, and at the same time, owing to the intimate contact between wire and sheath, the temperature is quickly taken up, an important feature often lacking with other constructions.

A novel form of resistance pyrometer has recently been proposed[1] in which **cupric or ferric oxides** are pressed into short porcelain tubes and heated to about 1,500° C. This has the effect of reducing the oxides to cuprous oxide or magnetite, respectively, which have the property of changing their resistance very greatly with temperature. A cuprous oxide rod formed in this way 0·6 cm. in diameter by 0·8 cm. long has a resistance of about 80,000 ohms at 0° C. and of 10,000 ohms at 300° C. A magnetite rod of the same dimensions has a resistance of 1,100 ohms at 0° C. and of 110 ohms at 100° C. Such a resistance, therefore, is about ten times as sensitive as one of platinum. Up to 500° C. or 800° C. these pyrometers appear to be reasonably constant, but sufficient information on this point is not at present available.

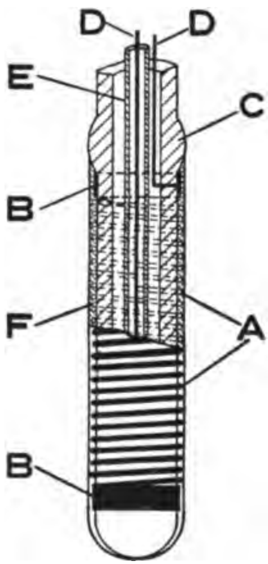


Fig. 181.—Silica Mounted Resistance Thermometer.

Since in every case the measurement of the resistance depends upon the passing of a current through the spiral, it is essential that the latter should have sufficient radiating surface to prevent any appreciable **rise of temperature from self-heating**. For high temperature measurements such disturbance need not be feared, but for low temperatures the use of platinum strip is to be recommended for open wound spirals (Fig. 180) both for this reason and also with

[1] See S. L. Brown, *Electrician*, Vol. 75, p. 549 (1915).

a view to its taking up the surrounding temperature as rapidly as possible.

Callendar has shown,[1] in this connection, that in the case of a resistance thermometer the usual rule for the **best arrangement of the arms of a Wheatstone bridge** does not apply, since the current flowing through the thermometer coil is the determining factor. He showed, moreover, that the best arrangement is to make the arms $a + b$ (Fig. 182) smaller than $c + d$ and to make a and c greater than b and d respectively, where d is the thermometer coil. As has been seen, it is almost essential to make c and d equal, but it is still preferable to make $a + b$ less than $c + d$, 1 : 3 being a convenient ratio. Under these conditions the best galvanometer resistance is twice that of d, and in any case it should lie between twice d and one-half of d.

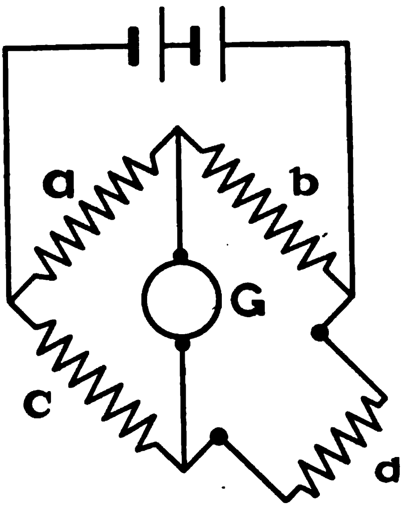


FIG. 182.—Fundamental Resistance Pyrometer Connections.

Thermo-electric Pyrometers.

The first practical thermometer based on the thermo-electric effect was that of **Le Chatelier**, who in 1886 used a thermo-junction of platinum and a platinum-rhodium alloy. Up to the present time no more suitable metals have been found for high temperature work. The E.M.F. of a thermo-electric couple is given by the equation—

$$\log e = \alpha \log t + \beta,$$

where e is the E.M.F. in microvolts, t the temperature of

[1] *Electrician*, Vol. 65, p. 855 (1910).

the junction in degrees Centigrade (assuming the "cold" ends of the junction to be at 0° C.), while α and β are constants having the following values :—

Platinum/platinum-rhodium (10 per cent.); $\alpha = 1{\cdot}19$; $\beta = 0{\cdot}52$
Platinum/platinum-iridium (10 per cent.); $\alpha = 1{\cdot}10$; $\beta = 0{\cdot}89$
Copper/Constantan . . . . ; $\alpha = 1{\cdot}14$; $\beta = 1{\cdot}34$

The following **couples** have, amongst others, been recommended and can be used for the maximum temperatures given, although, if continuously exposed to them, they are liable to deteriorate :—

Couple.	Maximum Temperature.
Carbon/graphite	2,000° C.
Platinum/platinum-rhodium	1,500° ,,
Platinum-rhodium (2 per cent.)/platinum-rhodium (10 per cent.)	1,500° ,,
Platinum/platinum-iridium	1,200° ,,
Nickel/nickel-chromium	1,100° ,,
Platinum/platinum-nickel	1,000° ,,
Iron/nickel	1,000° ,,
Iron-nickel/iron-nickel	1,000° ,,
Iron-nickel/Constantan	1,000° ,,
Nickel-chromium/Constantan	1,000° ,,
Iron/Constantan	900° ,,
Copper/nickel	700° ,,
Copper/Constantan	600° ,,
Silver/Constantan	400° ,,

The available E.M.F.'s are very small, but in the case of the so-called "base" metal couples are some five times as great as those of the platinum group. This is shown in Fig. 183 for a number of typical cases. The couples most used for high temperatures are platinum/platinum-rhodium (or platinum-rhodium (2 per cent.)/ platinum-rhodium (10 per cent.), which appears to be less subject to contamination than the pure platinum), and for low temperatures a Constantan/iron or nickel-chromium alloy. Of late years

the so-called "base metal" couples have been largely used up to 800° C. or even 1,000° C.; and although doubt has been thrown on their permanence, notably by Kowalke,[1] they have proved very valuable in industrial practice. Although the base metal couples have the advantage of a

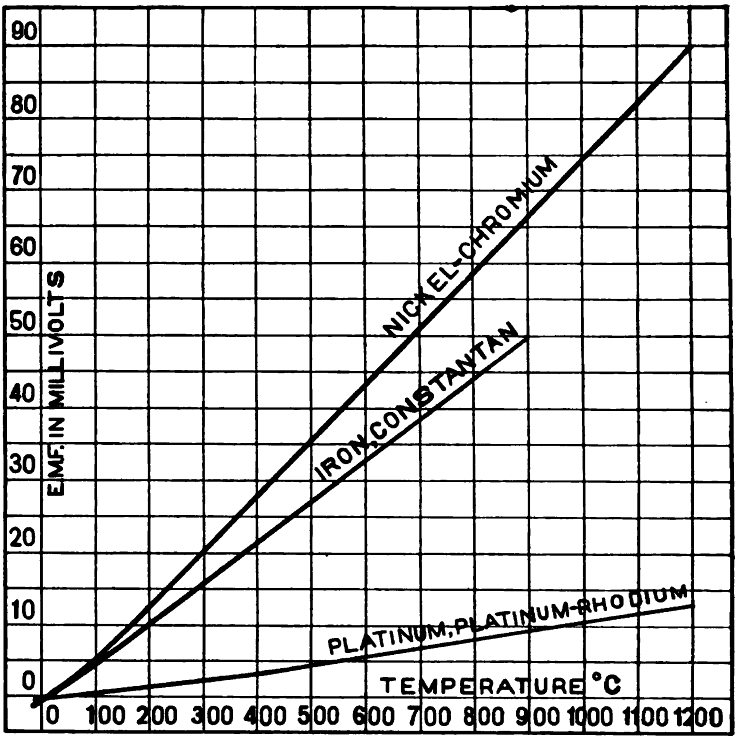


FIG. 183.—Some Temperature-E.M.F. Curves.

greatly reduced first cost, the platinum couples are more easily repaired, last longer, and have a considerable "scrap" value when worn out, so that the disparity in cost is not so great as it would appear at first sight. The carbon/graphite couple due to Bidwell [2] is still somewhat experimental, but

[1] *Transactions of American Electro-chemical Society*, 1913 and 1914.
[2] *Physical Review*, June, 1914.

appears likely to carry the range of direct pyrometry a stage further.

It follows from the smallness of the E.M.F. (see Fig. 183) that the **galvanometer** used must be extremely sensitive, and, moreover, in order that the resistance of the connecting wires (which varies with the surrounding temperature) may have a negligibly small effect, the internal resistance must be high. For this purpose a moving coil instrument is often used with either a suspended or very lightly pivoted coil carrying a pointer. The most accurate method, however, is by means of a potentiometer (see p. 111).

Reduced to its simplest form, the connections of a thermo-electric pyrometer are shown in Fig. 184, where T represents the thermo-junction, exposed to the temperature to be measured, and V the milli-voltmeter, graduated in temperatures. The precision possible with such an arrangement is, however, reduced by the fact that the other ends of the active wires A and B are joined together through the indicator V and so form a "**cold junction,**" the E.M.F. of which opposes that of the hot junction T. In fact, the indicator actually reads the difference of temperature between the hot and cold junctions instead of the temperature of the hot junction alone.

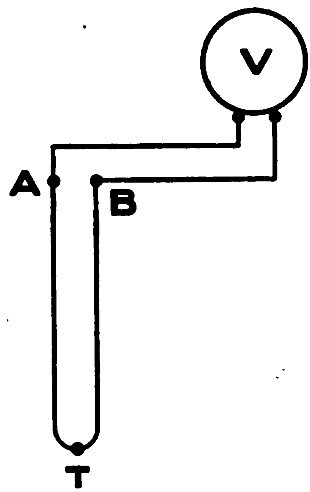


FIG. 184.— Fundamental Connections of Thermo-electric Pyrometer.

If the temperature of the cold junction is known, it can be deducted from that shown by the indicator, and some of the older pyrometers had mercury thermometers fitted in the head for this purpose. For high temperature work an average temperature (say 20° C.) is usually assumed in calibrating the indicator, and any

difference is unlikely to be large enough seriously to affect the accuracy.

For low temperatures some form of **compensation** is almost essential. One method consists in surrounding the pyrometer head, containing the junctions A and B, with a water-cooled jacket the temperature of which is known and constant. If a flow of water is not available, the " cold junction " may be kept at a constant temperature by immersion in a Thermos-flask filled with oil.

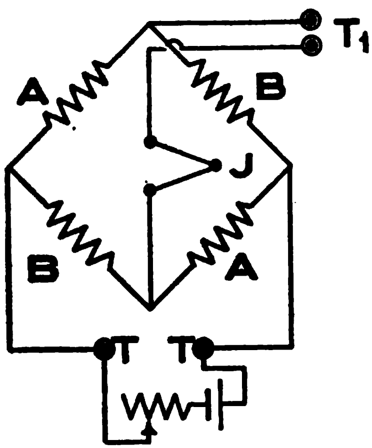


FIG. 185.—Compensation for Cold Junction Temperature.

Instead of deducting the temperature of the cold junction from the reading, the pointer of the indicator can be set round by means of the zero adjuster until, when disconnected from the thermo-couple, it stands on the mark corresponding to the cold junction temperature. So long as this remains constant the indicator will read correctly at all points.

An **automatic compensation** on these lines was first proposed by Darling, the principle of which is as follows. In the case of a base metal couple leads of the same metals can be led right back to the indicator, so that the cold junction is in effect carried back to the instrument itself. The outer end of the controlling spring, instead of being rigidly fixed, is attached to the end of a compound spiral consisting of two metals of different coefficients of expansion. Any change of temperature causes the free end of this compound spiral to rotate in the well-known way, and the end of the controlling spring is carried round with it. By this means it is possible so to proportion the parts that the pointer always stands on the scale at a point corresponding with the temperature of the interior of the indicator and, this being

the cold junction temperature, the readings become independent of the latter.

Fig. 185 shows a convenient, although slightly more complicated, method of compensation, due to Stroude and Josephs. The pyrometer head contains four resistances, A, A and B, B, arranged in the form of a Wheatstone bridge. One pair (B, B) is of manganin, and the other pair (A, A) of copper. The indicator is connected to the terminals T_1, and in series with it is the hot junction, as shown at J. A current is sent through the bridge by means of the battery and adjustable resistance connected to the terminals TT, and is adjusted to a definite value (say 100 milliamperes) by means of the indicator, which is used as a milli-ammeter for the purpose. When this current is flowing, the resistances are so proportioned that at a temperature of 20° C. (namely, that at which no compensation is required) the resistances A, A and B, B are all equal, so that the indicator receives no current except that due to the thermo-junction J. If the temperature of the head rises above 20° C., there will be a P.D. in the same direction as that due to J, and if it falls below 20° C., one opposed to that of J. The bridge resistances are so chosen that the P.D. is always just sufficient to deflect the indicator to a point on the scale corresponding to the temperature of the head, that is, of the cold junction. As has been shown, this is the condition required for perfect compensation.

By so choosing the values A, A and B, B that a current in opposition to the thermo-couple J flows through the indicator when the cold junction is at standard temperature any desired amount of "set-up" can be given to the scale, or, if desired, two ranges can be provided by the same means. For example, a single instrument can be given ranges of 0° to 1,000° and 500° to 1,000°, respectively, a combination which is often useful.

The remarks made when dealing with the **mounting and protection** of resistance thermometer coils apply equally to the mounting of platinum thermo-couples, the same materials being available. Base metal couples may be made

up in the form of wire, in which case the mounting and protection follows similar lines, but for high temperatures, an alternative arrangement, shown in Fig. 186, is to be preferred as being much more durable. The Constantan rod A is electrically welded on to the iron sleeve B, the space between them being filled with some heat-resisting material, such as asbestos, magnesia, or steatite. A couple so constructed can be used direct up to about 700° C., and will last for some time before the outer iron tube becomes so badly corroded as to affect the E.M.F. It is, moreover, inexpensive to replace. It must be remembered, however, that the precision attainable with a base metal couple is not nearly so high as with one of the platinum group.

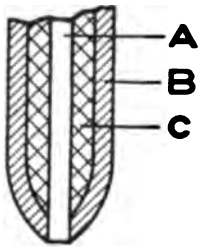


FIG. 186.—Base Metal Thermo-couple.

Radiation or Optical Pyrometers.

These instruments are not themselves subjected to the temperature to be measured, but only to radiation emanating from the hot body. They are valuable for extra-high temperature work, since the corrosive effect of a temperature of even 1,200° C. is such as rapidly to destroy any pyrometer subjected to it, more especially if active gases are present. With radiation instruments, on the other hand, there is practically no upper limit to the temperatures which can be measured, except for the difficulty of calibration, and the advances made in our knowledge of high temperature phenomena are continually raising even this limit.

Radiation pyrometers may be divided, broadly, into three classes, according as their action depends upon—

(1) The law of Wien connecting the temperature of a glowing "black body" with the intensity of one particular wave length given off by it.

(2) The law of Stefan and Boltzmann connecting the

temperature of a glowing "black body" with the total heat energy radiated from it.

(3) The colour of the light emitted by the hot body.

The intimate connection between the temperature of an incandescent body and its colour has been well known for centuries, but it is only quite recently that the method has been put on a scientific basis through the work of Paterson and Dudding.[1] For this reason radiation pyrometers of classes 1 and 2, although inherently more complex than those of class 3, were the first to be perfected.

Before dealing with the pyrometers themselves the laws alluded to above must be considered. It is well known that if a number of different substances are heated to the same temperature some will look brighter than others, *i.e.*, will radiate more energy. In a general way, the more "soot-like" the surface, the greater is the rate at which it will radiate energy, so that a theoretically perfect radiator is spoken of as a "**black body.**"

Lamp-black is the nearest approach to a "black body" at present known, although even this is not perfect. It should be added that the better a surface radiates, the better, also, it absorbs radiant energy, whether in the form of heat or light. A perfect "black body" will absorb all the radiant energy falling upon it. Everyday experience tells us that this is true in the case of light. For example, a surface covered with lamp-black absorbs nearly all the light falling upon it—that is, it looks "black."

Stefan and Boltzmann showed that the heat energy radiated per unit area of a glowing "black body" was directly proportional to the fourth power of its absolute temperature.[2] **Wien** further showed that if, of the energy radiated from a glowing "black body," only that of one particular wave length (*i.e.*, colour) was allowed to pass (the remainder being filtered out by means of a coloured glass),

[1] *Proceedings of Physical Society of London*, Vol. 27, p. 230 (1915).

[2] The absolute zero of temperature is − 273° C., so that the absolute temperature of a body less 273 gives its temperature on the ordinary Centigrade scale.

the intensity of the monochromatic portion bore a definite relation to the absolute temperature of the source.[1]

Although a true "black body" is not known, it can be shown that any substances contained in an **enclosure** the walls of which are at the same temperature throughout will behave as a "black body," so that both of the above laws are then applicable. An ordinary furnace and even

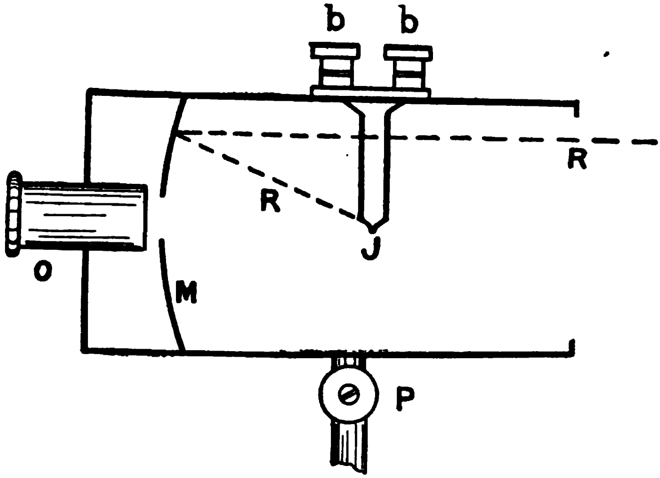


FIG. 187.—Féry Radiation Pyrometer.

a tube closed at one end and open at the other fulfil these requirements closely enough for all practical purposes.

Turning to actual examples of pyrometers, it will be more convenient to deal first with those based upon Stefan and Boltzmann's law. Of these probably the best known is that due to **Féry,** and Fig. 187 shows the arrangement in diagrammatic form. The open end of a short metal tube mounted on a hinged support at P is pointed towards the object whose temperature is to be measured by means of the eye-piece O, and rays from it are focussed

[1] Wien's law, as expressed by Planck, is as follows:—

Energy, of wave length λ, radiated per unit area at an absolute temperature, T, is—

$$A\lambda^{-5}(\epsilon^{B/\lambda T} - 1)^{-1},$$

where A, B, and ϵ are constants.

by means of an adjustable concave mirror, M, on to the thermo-junction J (as shown by the ray RR). This thermo-junction, which has a relatively high thermo-E.M.F., is covered with lamp-black, so that almost all the rays received are absorbed by it and converted into heat. By connecting a galvanometer to the terminals *bb* the temperature of the junction J can be measured, and will be proportional to the heat falling upon it, that is, to the heat radiated from the glowing source. But it has been said that if the latter can be regarded as a true "black body" the heat radiated is proportional to the fourth power of its absolute temperature, so that the galvanometer may be graduated in temperatures, direct.

It can be shown that, apart from absorption by the atmosphere, the readings are independent, within certain limits, of the distance between the instrument and the furnace. This follows from the fact that as the apparatus is brought nearer to the hot body the image of the latter increases in size, but not in intensity, so that so long as the instrument is near enough for this image to overlap the junction J the indications will be unaffected. This limiting distance, therefore, depends upon the size of the source, and is usually about thirty times the smallest diameter of the latter.

The indications are correct for "black bodies" only, but, as already mentioned, any substance in a nearly enclosed furnace is equivalent to such, so that this instrument can be used for the determination of temperatures in a large number of actual cases. In a good many other cases also, although "black body" conditions do not prevail, relative results are sufficient for the purpose, and can be obtained under existing conditions. The usual range is from 600° C. to 2,000° C., and for extremely high temperatures an adjustable sector is used which reduces the area of the open end of the tube by a given amount and so lowers the sensitiveness in the same proportion.

Foster some years ago devised an instrument based upon this principle, which he calls a "fixed focus pyrometer." The principle is shown in Fig. 188, although the tube is actually

much longer in proportion to its diameter. The hot body is represented by AB; M is the mirror, and J the thermo-junction. The heat received by J will be independent of the distance of the hot body from the pyrometer so long as the former is at least equivalent in dimensions to AB in each direction. This follows from the fact that the intensity of the radiation falls off as the square of the distance, but the solid angle subtended by the mirror increases in the same proportion, so that the total radiation received by J is unchanged.

A later modification of this idea is the " cone " pyrometer of Paul. In this instrument the mirror (M, Fig. 188) is

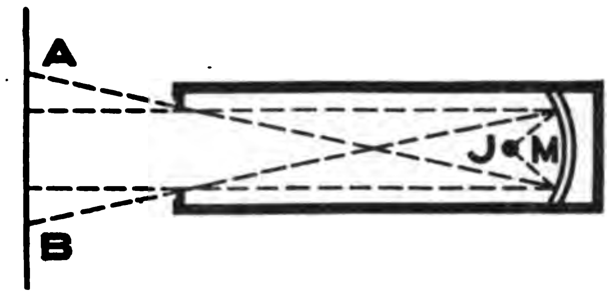


FIG. 188.—Foster Radiation Pyrometer.

replaced by a polished cone at the apex of which is placed the thermo-junction. The same considerations apply as regards the effect of distance, and as usually constructed both these pyrometers are available only so long as the hot body has a diameter of at least one-twelfth its distance from the mouth of the tube.

In a modification of the Féry pyrometer a compound spiral takes the place of the thermo-junction J in Fig. 187. The spiral is constructed in the well-known manner of two metals having different coefficients of expansion. A pointer attached to the free end of this spiral moves over a scale. The mirror concentrates the radiations received from the hot body upon the spiral, and its temperature is thereby raised and a deflection produced on a scale graduated in temperature. This pyrometer is convenient to use, but is

much less sensitive and accurate than the thermo-junction pattern.

Special cases often arise in which a radiation instrument cannot be used direct. For instance, the temperature of a furnace which cannot be opened may be required, or of a mass of molten metal covered with slag. In such cases a porcelain or other refractory tube closed at one end can be built into the furnace or plunged into the crucible, as the case may be, and the interior of the tube sighted through its open end. In some cases it is convenient to attach the

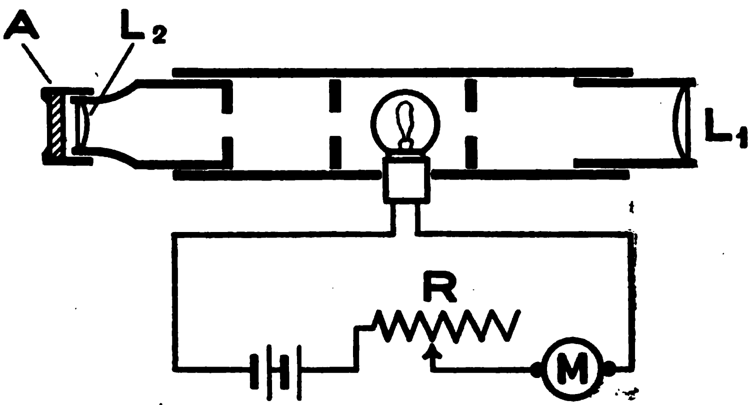


FIG. 189.—Holborn and Kurlbaum Pyrometer.

tube to the pyrometer itself so as to form one unit for handling.

Of the pyrometers based on the law of Wien (class 1, p. 304) the best known is probably that due to **Holborn and Kurlbaum.** It is shown in Fig. 189. The telescope is focussed on the hot body by means of the two lenses L_1 and L_2, and the filament of the incandescent lamp shows up against the glowing body as a background. A red glass, A, cuts off nearly all rays except those of a given wave length (say $0{\cdot}65\,\mu$), and the resistance R is varied until, under these conditions, the filament and its background appear to be of equal brightness. When this is the case, the intensity of radiation (*i.e.*, the energy radiated per unit area) is the same for the filament as

for the hot source, and provided each can be looked upon as a "black body," Wien's law shows them to be at the same temperature. It only remains, therefore, to draw up a table connecting the temperature of the filament with the current flowing through it (as shown on the ammeter M), and the instrument is available for measurements up to the limit to which it is safe to run the lamp. Since constancy is essential to accuracy, it is not advisable to push the lamp to a very high temperature, and this can be obviated by reducing the intensity of the source in a known ratio by means of neutral-tinted glasses placed in front of the lens L_1.

For the lowest temperatures, say 600° C. to 800° C., the red glass can be omitted to advantage without loss of accuracy, since the radiation is almost entirely from the red end of the spectrum. Up to 1,200° C. one red glass is used, and above this it is advisable to use two, so as more effectually to filter out all rays but the red.

In another pyrometer, that due to **Wanner,** the lamp is kept at full incandescence throughout, and the intensity of the light coming from the hot body is varied by means of a polarising arrangement until a balance has been obtained. A disadvantage of this method lies in the considerable loss of light, even when set in the brightest position, so that measurements below 900° C. are difficult to make. Moreover, the light emitted by an incandescent source is usually slightly polarised, and considerable errors may arise from this cause.

The same remarks as to "black body" conditions apply to both these pyrometers as to those of the total radiation class already described (p. 307). Apart from the possible disadvantage of depending upon a zero method, the Holborn-Kurlbaum pyrometer is a valuable one, and is capable of very considerable precision in skilled hands. It has a useful range of, say, 1,000° C. to 4,000° C.

As already stated, the intensity of the radiation emitted depends upon the nature of its surface (being greater the "blacker" it is); but **Paterson and Dudding**[1] have shown that the *colour* of the light is almost independent of the

[1] *Proceedings of Physical Society of London*, Vol. 27, p. 230 (1915).

nature of the surface. Sufficient data are not at present available to say definitely for what substances this is strictly true, but it certainly applies to those as widely different as carbon, tungsten, and platinum, and it seems probable that it holds good for all metals, besides substances, such as carbon, which approach the true "black body" in character. Hence it follows that pyrometers based upon this method are not only available for all cases to which those based upon methods 1 and 2 are applicable (which in practice means to closed furnaces only), but can be used in a very large number of cases where the latter are inapplicable.

The method adopted consists in allowing light from the source whose temperature is to be measured to fall upon one screen of a photometer, while light from a calibrated source falls upon the other. The latter is adjusted until the colours are the same, and, as it has been shown that under these conditions the temperatures are identical, that of the source is therefore known.

The calibrated source consists of a carbon or metal filament incandescent lamp, the colour being adjusted by means of a rheostat and ammeter. With a carbon filament, temperatures from 1,600° C. to 2,200° C. can be measured, and with a metal filament up to 2,500° C. The former has the advantage of giving a more open scale of current.

Graphic Pyrometers.

Resistance and thermo-electric pyrometers, as well as to a limited extent radiation pyrometers, can be constructed of the graphic pattern. The power available for the working of the recording mechanism is necessarily small, so that some form of relay or point-by-point instrument is almost essential. For a description of some which are available see p. 359. Owing to the fact that the temperature changes comparatively slowly, in nearly all cases, there is no disadvantage in a point-by-point grapher, such as the thread (p. 359) or inkless (p. 355) forms; and although relay instruments of the Callendar pattern (p. 359) have been extensively used in the past, they are now largely giving place to the others.

In many cases, it is wished to obtain a graphic record from a number of thermometers on a single chart. This can be done by employing a clock-driven commutating switch which connects each of the thermometers to the grapher in turn for a minute or two at a time. It is possible in this way to obtain two or even four records on one chart, and by employing a two-colour arrangement as many as eight records can often be made without confusion. The possible number depends, however, very largely upon the character of the records, that is, whether they are comparatively steady and, above all, whether they are likely to lie one upon the top of the other.

Instrument Transformers.

Transformers, in the case of alternating current instruments, may be regarded as taking the place of the multiplying resistances or shunts commonly employed with continuous current. The reasons for the use of instrument transformers can be stated as follows :—

(1) **The avoidance of high tension in the instruments.** The latter do not conveniently admit of being insulated for working pressures of more than, say, 1,000 volts.

(2) **To permit of the use of convenient instrument windings.** The values almost invariably adopted are 110 volts and 5 amperes, at the normal circuit pressure and full load current respectively.

(3) **To give greater elasticity in placing the instruments,** since only small wires need be led to them. This enables the wiring of the switchboard to be simplified, and the instruments to be placed in any convenient position. In modern high tension practice the transformers are usually grouped with the oil-immersed switches in fireproof cubicles, while the switchboard carries only the instruments and controlling switches, no high tension leads being brought to this board.

In designing instrument transformers, therefore, the following points are of the utmost importance:—

(1) Insulation.

(2) Correctness and constancy of ratio under all load conditions.

(3) In the case of wattmeters, etc., phase agreement between primary and secondary.

The subject of **insulation** is of extreme importance. Instrument transformers do not differ greatly from power transformers in this respect, except that a rather higher margin of safety is commonly allowed in the case of the former, and the pressure test recommended is (pressure to earth $\times$ 2·25) + 2,000 volts.

The more usual forms of insulation are micanite, pertinax, or a similar material, between primary and secondary, with end cheeks, often of wood thoroughly dried and impregnated with varnish *in vacuo*. Some makers use a one-piece porcelain spool for the primary windings of current transformers. This is effective, but not so universally applicable as the other methods. For extra-high tension work (say above 7,000 volts) the usual practice is to immerse the transformer in a tank filled with oil or insulating (cable) compound, the ends of the windings being brought out to porcelain insulated terminals, fixed to the lid or sides of the tank.

As regards the question of variation in the **ratio of transformation,** in the case of a voltmeter or ammeter it is usually possible to calibrate the instrument with its transformer, thereby avoiding the effect of ratio variation, although in modern practice it is rarely necessary to adopt this expedient. Constancy of ratio within close limits is essential for operating wattmeters and, still more, watt-hour meters, so that it is preferable to make all transformers in such a way that within specified limits of load and frequency a definite ratio of transformation is ensured. For all ordinary purposes the instruments may then be calibrated independently of the transformers.

Pressure Transformers.

The vector diagram for a pressure transformer is given in Fig. 190. Commencing from the magnetic flux Φ and assuming, for simplicity, that the primary and secondary windings have an equal number of turns, the vectors E_1 and E_2 may be drawn at right angles to Φ, to represent the E.M.F.'s induced[1] in the primary and secondary windings, respectively. If the secondary of the transformer is on open circuit, the primary current will be only that required to produce the flux, and supply the iron losses. This no-load current, I_0, will, therefore, be made up of the magnetising current I_M, in phase with Φ, and the iron loss current I_L, at right angles to it. When the transformer is loaded this no-load current may be considered as a component of the total primary current.

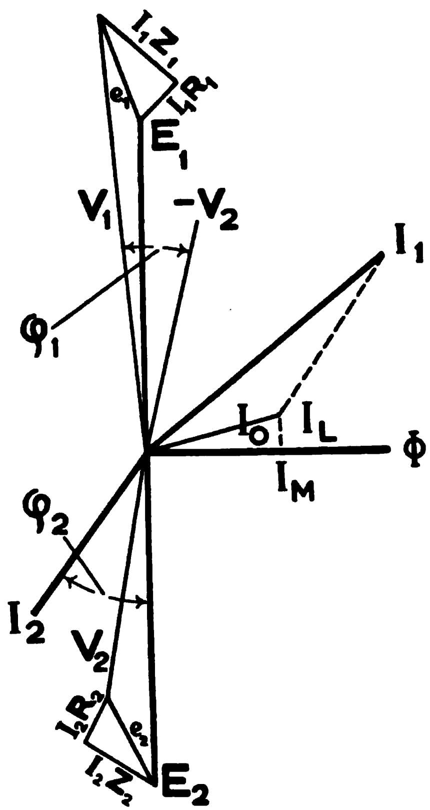


FIG. 190.—Vector Diagram of Pressure Transformer.

Let the secondary load current be I_2, lagging by an angle, φ_2, behind the secondary E.M.F. E_2. To balance this, there must be a corresponding primary current

[1] $E = \Phi \times \text{frequency} \times \text{turns} \times \frac{4{\cdot}44}{10^8}$.

added vectorially to the no-load current, giving the total primary current I_1. Assuming further that the primary winding has a resistance, R_1, and an inductance, Z_1 (due to that part of the primary flux which does not link with the secondary turns), a vector triangle can be constructed giving e_1 as the total pressure drop in the primary. Adding this to E_1 (the back E.M.F. of the primary), V_1 is obtained as the total pressure applied at the primary terminals. By similar reasoning with reference to secondary resistance and impedance (Z_2 depending on the secondary flux, which does not link with the primary) V_2 is found for the pressure at the secondary terminals.

Transformers are usually connected so that the secondary voltage appears to be in the same direction as the primary instead of in opposition, so that for practical purposes the vector V_2 is reversed, as shown at $-V_2$. It is then evident that the transformation ratio will differ from the ratio of primary to secondary turns by the difference in length between V_1 and $-V_2$. There will also be the difference of phase shown by φ_1.

In practical working, there are two variable quantities to be considered, viz., the primary applied pressure V_1 and the impedance of the secondary or load circuit (I_2 E_2). It is unimportant whether the voltage ratio agrees closely with the ratio of turns or not, provided that it is but little affected by changes in these quantities. **Variation of primary voltage** is almost equivalent to changing the scale of Fig. 190, excepting for the vectors representing the magnetising and losses currents (I_M and I_L). As a result, the ratio of primary to secondary volts usually tends to increase both at very low and very high voltages, but the variation in a well-designed transformer is extremely small and should not exceed 0·2 per cent. between 10 per cent. and 130 per cent. of the normal voltage, and is, for most purposes, negligible.

It will also be found that the phase difference between primary and secondary terminal voltages, though always extremely small, varies somewhat and is liable to become excessive if the voltage is raised to such a point that the core

flux density exceeds about 13,000 lines per square centimetre (maximum) at normal frequencies. The curves I. and II. in Fig. 191 show the way in which the magnetising current varies with the flux density, while curves III. and IV. show the corresponding iron losses. Fig. 192 illustrates the effect on the ratio and phase difference.

Alteration of **secondary load** is more serious in its effect

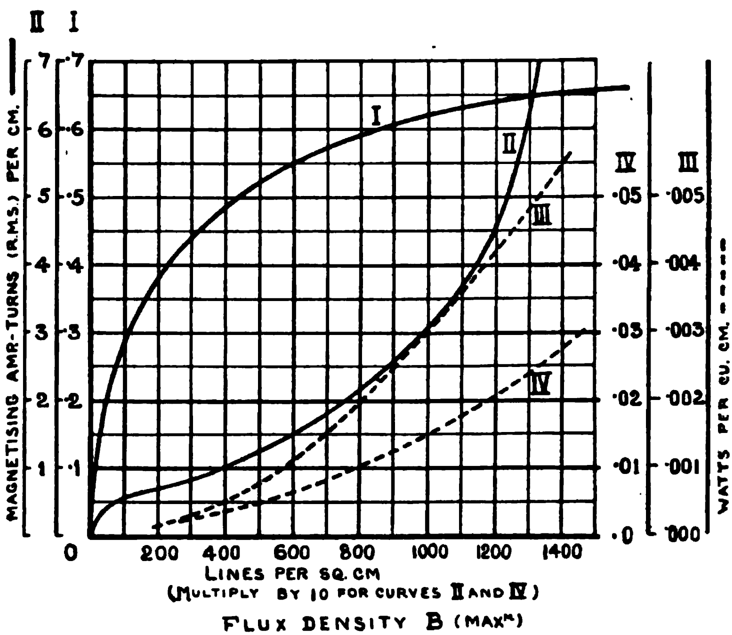


FIG. 191.—Magnetising Current and Iron Loss Curves for Silicon Steel.

both on ratio and phase displacement; and if the highest accuracy is desired, the secondary load should not differ greatly from that at which the instruments were calibrated with the transformer.

It is well known that the internal voltage drop of a pressure transformer is dependent upon both the magnitude and phase of the secondary current. Referring again to Fig. 190, it will be seen that any variation in the secondary load will affect the lengths of the vectors e_1 and e_2 and, therefore, to

a small extent, the ratio and phase of V_1 and V_2. In Fig. 193 the results of some actual tests are given, showing the regulation which may be expected.

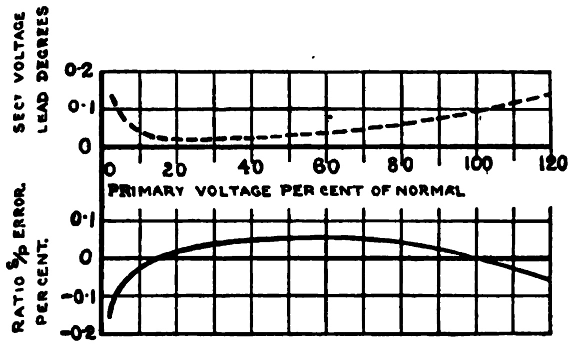


FIG. 192.—Ratio and Phase of Pressure Transformer as affected by the Applied Pressure.

It will be clear from what has been said that the features in the design which tend to close regulation are—

(1) Low resistance of the windings.

(2) Small magnetic leakage between the windings.

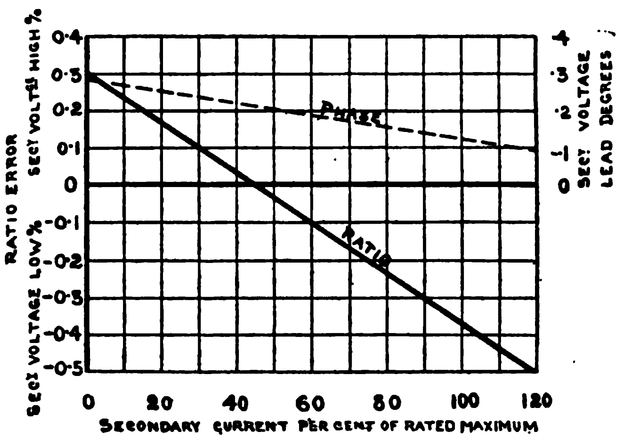


FIG. 193.—Ratio and Phase of Pressure Transformer as affected by the Secondary Load.

The first is of especial importance when the secondary load is non-inductive, and the second when it is inductive.

The variation of secondary voltage with the load forms a convenient criterion by which to rate pressure transformers, the power factor of the load being usually specified as unity or sometimes as 0·8 lagging. A voltage drop of 1 per cent. between open circuit and the rated secondary load may be considered satisfactory. The question of heating can usually be neglected in pressure transformers, the actual load which can be carried without overheating being in most cases five or ten times the maximum allowable on the basis of constancy of ratio.

The **phase displacement between the primary and secondary voltages** also depends upon the internal voltage drop, so that the phase displacement is roughly proportional to the secondary current. Fig. 193 illustrates the results of some actual tests on this point.

Current Transformers.

The vector diagram for a current transformer is shown in Fig. 194, and is similar in construction to that given in Fig. 190 for the pressure transformer, except that the primary applied voltage has been omitted. Assuming equality of turns, the primary current I_1 may be regarded as being made up of a component, $-I_2$, balancing the secondary current I_2, and the no-load current I_0 (the latter being made up of the iron loss and magnetising components, I_L and I_M, respectively). The construction of this diagram will be understood by a reference to the description of Fig. 190 on p. 314. In the diagram, the reversed secondary current I_2 leads, as compared with the primary current I_1, by an angle, φ_1, and this is usually the case. If the secondary load is very inductive (*i.e.* if φ_2 is large), it is possible for the vector I_2 to be brought into direct opposition to the no-load current I_0, and, therefore, to I_1, so that the phase displacement between primary and secondary currents disappears. A still greater lag in the secondary causes the secondary current to lag behind the primary instead of leading. This condition, however, rarely occurs in practice.

It is not usually essential for the transformer ratio to

be the same as the ratio of turns, nor in all cases that the primary and secondary currents should be precisely in phase, but it is important that the current ratio and phase displacement should be sensibly constant throughout the working range. If this is to be secured, the vector diagram of Fig. 194 must remain unaltered (except as to scale) throughout the range of current to be dealt with.

Now, assuming the impedance of the secondary circuit, including the winding, to be constant, E_2 varies with I_2, and

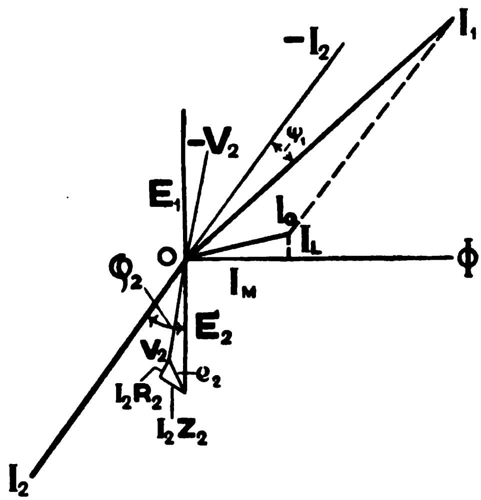


FIG. 194.—Vector Diagram of Current Transformer.

so, therefore, does Φ. For the vector diagram to remain unchanged, except in scale, I_M and I_L must vary as E_2. But E_2 is proportional to Φ, and consequently it is essential that I_M should be proportional to Φ or B. For the same reason I_L must vary as Φ, or the core loss in watts as Φ^2 or B^2 (since core loss $= I_L \times E_1$).

In practice, the magnetising current is by no means proportional to B, except at low inductions (see Fig. 191), and the core loss varies[1] in a somewhat irregular manner

[1] For a detailed discussion of this point see Agnew, *Bulletin of Bureau of Standards* (U.S.A.), Vol. 7, No. 3 (1911).

between the powers of 1·5 and 2·5 of B. The exponent depends upon the brand of iron and range of flux densities used, 1·6 or 1·7 being a usual value. In that case the core loss current I_L, instead of being proportional to B, is more nearly proportional to $B^{0 \cdot 8}$.

Referring again to Fig. 194, it is evident that if the secondary load is highly inductive (*i.e.*, if φ_2 is large), the effect of the core loss component (I_L) on the current ratio $\frac{I_2}{I_1}$ is small, whereas that of the magnetising current (I_M) is considerable, since it is more nearly in line with I_1. It has been seen that the losses component I_L varies much more nearly in the desired way than does the magnetising component I_M, so that a lagging secondary current is usually accompanied by increased ratio variation. At the same time the phase difference between primary and secondary currents decreases (see p. 318).

The art in designing satisfactory current transformers lies, therefore, in reducing I_L and I_M to the smallest possible dimensions and so selecting the iron and range of flux densities as to make I_L and I_M vary nearly as B. To this end the best quality of iron must be employed, a very good material in this respect being the silicon steel known as stalloy.[1] A low flux density is also essential, the upper limit for current transformers working wattmeters being about B = 1,500 lines per square centimetre (maximum). With regard to the way in which the magnetising and iron loss components vary with the secondary current very little can be done, but it may be observed from Fig. 191 (p. 316) that in the iron mentioned the core loss current is approximately proportional to the flux density (the watt loss being roughly proportional to the square of the density) over the working range.

The shortest **magnetic circuit**, without joints if possible, is also essential, to reduce I_M. With reference to the best proportions for the copper and iron employed, it will be

[1] This material also possesses considerable advantages for the cores of pressure transformers. The curves in Fig. 191 refer to this steel.

observed that if the iron section is reduced a corresponding increase in the number of turns is necessary in order to keep the flux density within the prescribed limits.[1] This will automatically reduce the fraction of the total primary current required for magnetisation and iron losses, since the ampere-turns devoted to these are unaffected. It is, therefore, a useful expedient up to the point where the resistance and inductance of the secondary winding become of greater importance than the corresponding quantities of the load. This usually means that a well-designed current transformer will have from 600 to 1,200 ampere-turns on the primary at its rated full load current. There is no objection to increasing the upper limit to almost any extent when the current to be measured exceeds 1,200 amperes, but there is no advantage in doing so for smaller currents, and the cost of construction is increased. These figures refer to transformers intended for a secondary load of from 15 to 40 volt-amperes at normal full load current and at a frequency of 50. For other frequencies the permissible volt-ampere load varies in direct proportion with it, and for heavier loads an increase in the ampere-turns is desirable.

Secondary magnetic leakage in a current transformer shows itself as an increase of I_2Z_2 (Fig. 194), and results in an increase of E_2 (for a given V_2) and with it of I_L and I_M, thus adversely affecting the accuracy. Any increase in the secondary resistance or reactance has a similar effect. It should be observed that a leakage of primary flux (which fails to cut the secondary winding) is without effect except in so far as it may vary with the load. The leakage now referred to is that of the secondary flux, which fails to cut the primary winding.

In Fig. 195 are given the results of some tests on a typical current transformer at different frequencies and loads. The ratio error is too small at any point to be measured accurately by means of ammeters in the primary and secondary, and it was determined by a differential wattmeter

[1] $E = \Phi \times \text{frequency} \times \text{turns} \times \frac{4{\cdot}44}{10^8}$.

method, somewhat similar to that originally devised by Drysdale.[1] The phase displacement was measured by the same method. A displacement of 0·3° corresponds, it may

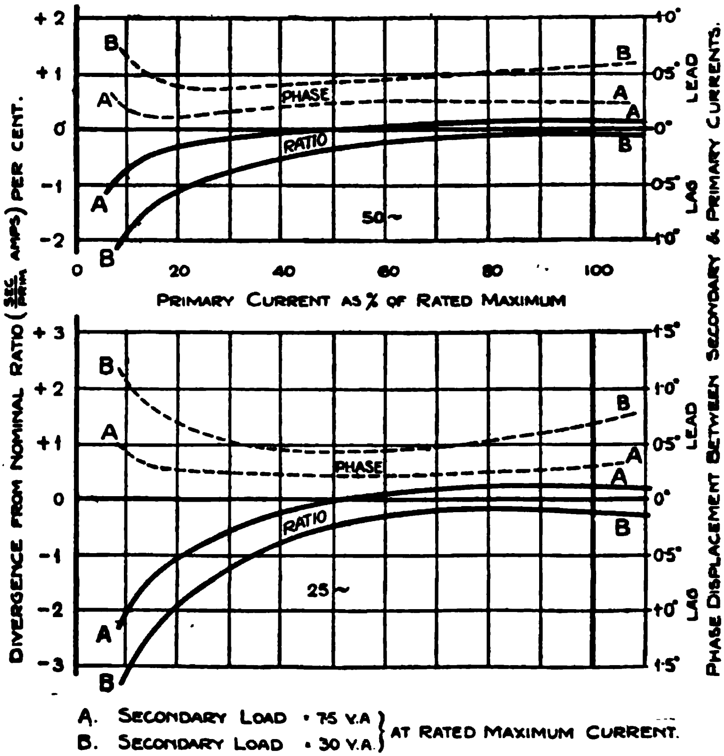


FIG. 195.—Ratio and Phase Curves of Current Transformer.

be noted, to a wattmeter error,[2] at 0·5 power factor, of 0·5 per cent. of the volt-amperes passing.

The change of ratio and phase angle with the resistance or **impedance of the load** becomes important as limiting

[1] See p. 338.

[2] Since the secondary current leads as regards the primary, it follows that for a wattmeter to read correctly when fed through a current transformer the pressure flux must lead as regards the pressure. This can only be done in the case of a dynamometer wattmeter (p. 209) by the use of a condenser, but is readily arrived at with the induction pattern (p. 225) by making the pressure circuit less inductive than would otherwise be necessary.

the number of instruments which can be connected to the secondary. Fig. 196 shows the behaviour in this respect of the current transformer previously mentioned. The effect of **changes of frequency** or wave form in a well-designed current transformer is small. If the secondary load is very inductive, the effect of change of frequency is less noticeable than with a non-inductive load, since in the former case the reactance voltage increases with the frequency, so that at any particular secondary current the core density remains approximately constant, and, as was previously pointed out

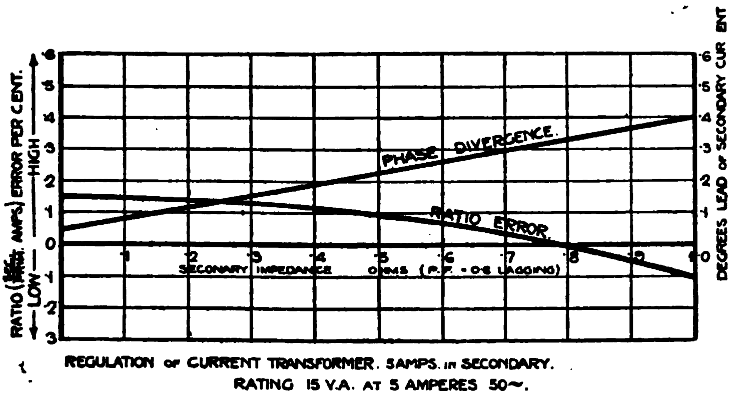


FIG. 196.—Ratio and Phase Curves of Current Transformer.

(p. 320), if φ_2 is large the effect of I_L on the ratio is small compared with that of I_M.

The curves given in Fig. 195 were taken at 25 and at 50 cycles per second with the same secondary load. This consisted, in the case of curves A, of the coils of the dynamometer wattmeter used for the test, while in obtaining the curves B the coils of a number of induction type relays were added in series. In common with potential transformers, it may be noted that current transformers are affected more by the volt-ampere capacity of the load than by the watts. For this reason the limits of variation of ratio are usually specified in terms of a secondary terminal voltage and current.

General.

With transformers built from some of the ordinary kinds of iron, such as Swedish charcoal, there is an appreciable **increase in the iron loss after the transformer has been in use for some time.** As a result, the performance is adversely affected with regard to both ratio and phase displacement. Stalloy, on the other hand, is almost free from this objection, but if much work is done on the iron in cutting or stamping the laminations, it is well to reanneal it before assembling. If this is neglected, the losses may actually become less after the iron has been in use for some time, owing to partial annealing.

It will also be found that if the core should become saturated (say, through opening the secondary circuit of a current transformer while in use) the losses are appreciably increased. This defect may cure itself with continued use, the losses returning to their original value. (See also under "Heating," below.)

Attention has been drawn by Hunter [1] to another effect of the saturation of the iron which occurs in the event of a severe short circuit. During the peak of each cycle the iron becomes highly saturated, and the voltage drop over the primary winding is increased accordingly. As a result the **pressure between turns may increase enormously**, sometimes, in fact, to such an extent as to break down the insulation. In the case of a current transformer feeding a protective relay such a breakdown may have serious results, and should be guarded against by efficient insulation between turns. A safety gap separated by paper is sometimes provided as an additional safeguard.

As was mentioned (p. 318) in the case of the pressure transformer, it is not usually possible to work anywhere near the **heating limit.** A fairly high current density (say 1,000 to 1,200 amperes per square inch) is usually desirable in the primary winding of a current transformer, since this leads to economy of space and, therefore, to a shorter magnetic

[1] P. V. Hunter, *Journal Inst. E.E.*, Vol. 54, p. 109 (1915).

circuit and with it increased accuracy. Such a transformer, on account of its negligible iron loss, will usually work for an indefinite period at 80 per cent. overload without excessive heating. A point of some importance is that, should the secondary be open-circuited, the whole primary current represents magnetising current and the flux density rises to saturation point. Under such circumstances the iron losses are apt to cause excessive heating, and cases have occurred of transformers being burnt out in this manner. Moreover, such saturation interferes with the accuracy, and a transformer which has undergone a severe short circuit, or, still more, has had its secondary open-circuited while under load, should be demagnetised by passing a current through the primary and gradually reducing the secondary resistance from a fairly high value to zero. A similar saturation of the iron may arise, as has been said, in the event of a heavy short circuit, but such abnormal currents are usually of short duration and therefore not serious from the heating point of view. In fact, the mechanical stresses due to severe overloads are often more dangerous than the heating effects, but a well-designed current transformer must withstand many times the full load current, provided the secondary is practically short-circuited.

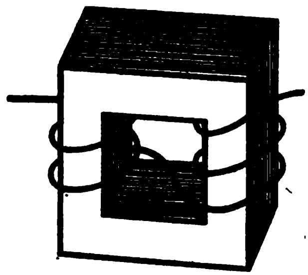


FIG. 197.—Double Coil Instrument Transformer.

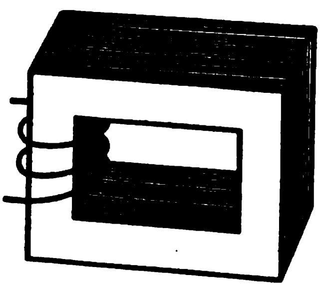


FIG. 198.—Single Coil Instrument Transformer.

The most satisfactory **form of magnetic circuit** is usually a compromise between the ideal[1] and one determined entirely by considerations of manufacture. For pressure transformers the rectangular form shown in Fig. 197 is

[1] See W. E. Burnand, *Electrician*, April 9th, 1915.

probably the best. As an alternative the windings may be placed on one limb only, as shown in Fig. 198, but this gives a somewhat longer magnetic circuit and is not so economical. Another design is the H or shell type, shown in Fig. 199. It is rather more troublesome to assemble, but

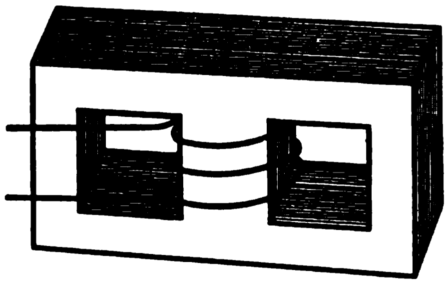


FIG. 199.—Shell Type Instrument Transformer.

the windings are better protected mechanically than with either of the preceding.

For current transformers a simple ring composed of laminations, as shown in Fig. 200, is a good form. It is particularly well suited to use with a primary

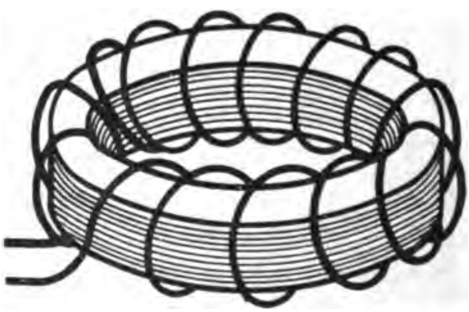


FIG. 200.—Ring Type Instrument Transformer.

consisting of a round bar or cable. It can also be adapted to a wound primary in the manner shown in Fig. 201, which represents a construction due to the British Thomson-Houston Company. Fig. 202 shows a complete current transformer with a core of the type

illustrated in Fig. 198. In the case of a transformer with wound primary this form is preferable to that shown in Fig. 197, on account of the increased difficulty of insulating heavy windings when two spools are employed. For slipping

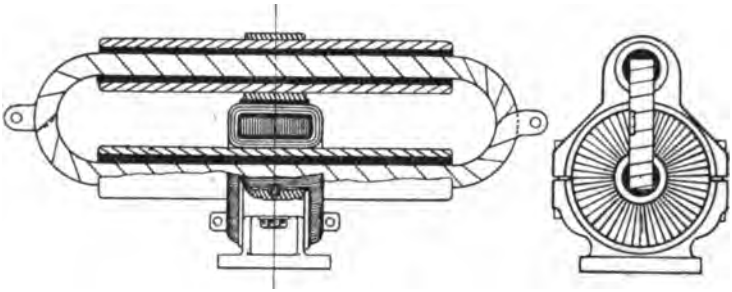


FIG. 201.—E.H.T. Ring Type Current Transformer.

over bus-bars, etc., the types shown in Figs. 197, 198 or 200 are suitable. If the single coil type (Fig. 198) is employed for this purpose, the primary bar should be clamped as near to the secondary as possible, and the relative positions

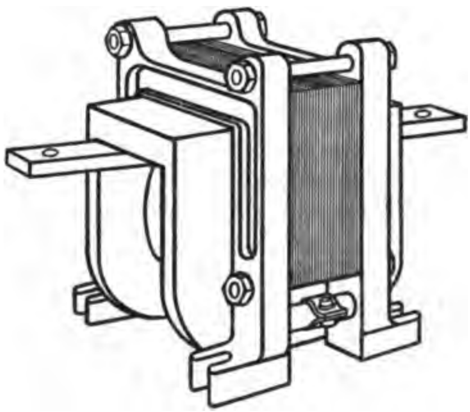


FIG. 202.—Medium Pressure Current Transformer.

of primary and secondary windings should not be altered after the ratio has been adjusted.

The H type shown in Fig. 199 is a useful alternative to the simple rectangular frame (Fig. 198). It is, however, more

expensive to wind, and does not lend itself to those cases in which a bar primary is required. Theoretically the slightly better magnetic circuit which it affords is an advantage, but as usually constructed this is largely counterbalanced by the reluctance of the extra joints.

Current transformers are sometimes required to **surround a cable or bus-bar which cannot be cut**. For this purpose the magnetic circuit is made in such a form that it can readily be opened and reclosed round the bar or cable, the form shown in Fig. 197 being a suitable one. The adoption of two secondary coils is advisable, to minimise the effect of neighbouring conductors, and the reluctance of the joints should be reduced to the least possible value. A butt joint is objectionable, but, if it cannot be dispensed with, should be made of larger area than the remainder of the core (see Fig. 203), and must have accurately planed surfaces, while a hinged joint should be interleaved.

For general testing purposes a transformer has been developed on the lines of that just described, but provided with a spring hinge and a pair of handles, by means of which it can be opened and allowed to close round the conductor to be investigated (Fig. 203). To the secondary, may be connected either a telephone for the detection of very small currents or an alternating current ammeter. Owing to the reluctance of the joints, great accuracy is not to be expected, but as a rough gauge such an instrument is often useful. It is, of course, only available for use with single core cables, but it is of interest to point out that the accuracy is not seriously affected by the cable being steel or iron armoured.

For **multiple range current transformers** the secondary winding may be provided with a number of tappings, so that a change of range can be effected without interfering with the primary connections. This arrangement has the disadvantage, however, that the errors differ on the various ranges, since the ampere-turns and flux density are different. To secure completely consistent behaviour on the different ranges, the primary should be subdivided and the sections arranged for grouping in series or parallel, as desired.

This arrangement usually meets the requirements of multiple range transformers for use in connection with portable testing instruments, as a change of range during a test is not often necessary.

A more usual construction employs a number of distinct primary windings, each giving one of the ranges required. This arrangement is convenient, but owing to the large amount of space occupied by the spare windings, it is difficult to obtain the large number of ampere-turns upon which, as has been seen, accuracy so largely depends.

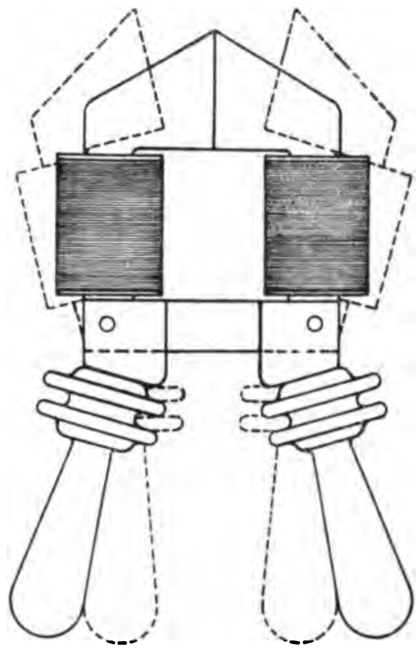


Fig. 203.—Current Transformer with Hinged Core.

A further multiple range device, applicable to portable transformers, embodies a primary winding consisting of a reasonable length of flexible cable which can be wound on by hand, so as to give a number of turns appropriate to the range desired. Thus, suppose the secondary is wound to correspond to 1,000 ampere-turns at full current, it will merely be necessary to wind ten turns on the primary to measure up to 100 amperes, five turns to 200 amperes, two turns to 500 amperes, and so on. The best form of core for this purpose is that of Fig. 198 or Fig. 200. By providing a number of lengths of flexible cable a wide choice of range can be obtained on a single transformer, with the certainty that the ratio and phase displacement curves will be almost identical.

Pressure transformers should always be **protected by fuses** on the high tension side. These protect the system against faults within the transformer or in the instruments connected to it. They do not, however, protect the transformer itself against overloads, and to this end it is advisable to instal fuses on the low tension side also. These have the further advantage that they can readily be withdrawn should it be necessary to carry out alterations to instruments or wiring while the transformer is alive.

In order to **protect instrument transformers against surges,** it has been proposed to connect resistances in series with the primaries of pressure transformers or in parallel with those of current transformers. The value of the resistance recommended is such that it absorbs about 0·1 per cent. of the pressure or current, as the case may be, and is then said to introduce a ratio error of less than 0·25 per cent.[1] A resistance constructed of Silit has been proposed, as this substance has the property of decreasing in resistance if a high pressure is applied to its terminals, and it thus more readily dissipates the energy of a surge. Such resistances are liable to permanent charges, however, and a wire resistance is to be preferred. A choking coil connected in series affords further protection. A condenser connected across the current transformer terminals has also been proposed, but is of doubtful efficacy. It may be noted that a non-inductive shunt on the primary of a current transformer has a tendency slightly to reduce the phase displacement and is beneficial to that extent.

It has been assumed in the foregoing that there was a separate transformer for each instrument or group of instruments. A simplification of the **connections** can often be made by working a number in combination on a polyphase system. The following are typical of what may be done in this direction :—

Two single phase transformers may be connected across the lines of a **three-phase circuit,** as shown in Fig. 204. The secondary pressures at *ab* and *bc* are similar in phase, as

[1] See Gewecke, *Electrotechnische Zeitschrift*, Vol. 35, p. 386 (1914).

well as proportional in magnitude, to the primary pressures at AB and BC, and a third transformer for the phase AC is, therefore, unnecessary. If a secondary pressure in phase with that between one line and the neutral is required, it may be obtained by connecting the instrument circuit between the outer terminal of one secondary and the middle point of the other, *e.g.*, between *a* and *d* (Fig. 204). Another method which gives the same result is shown in Fig. 205, in which the secondary of one of the transformers is reversed

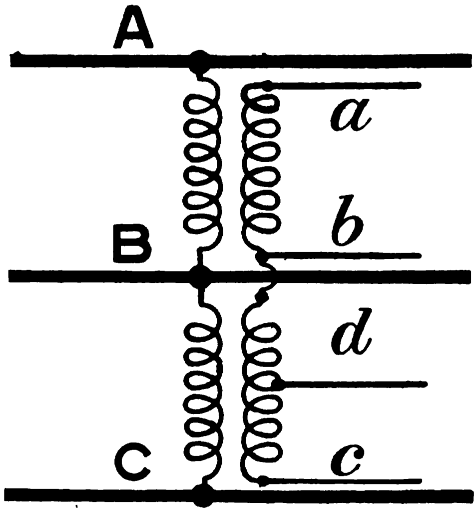


FIG. 204.—Two Pressure Transformers on a Three-phase System.

and thus gives a pressure between *a* and *c′*, which is in phase with that between B and the neutral point of the system. With the first arrangement the voltage will be 0·866 times the secondary line voltage and therefore 3/2 times the voltage from line to neutral. With the second method the voltage obtained is $\sqrt{3}$ times the secondary line voltage or three times that between line and neutral (see also Fig. 150).

Three-phase pressure transformers are often used when a secondary neutral point is required. In this case the secondary windings are Y-connected, and the neutral point

of the primary, if Y-connected, may, to advantage, be joined to that of the system.

Owing to the fact that a triple frequency current cannot flow in an insulated Y-connected three-phase transformer or in three separate transformers so connected, it was shown by Clinker[1] that a distorted flux wave was produced, and with it a distorted secondary pressure wave. Unless, therefore, the neutral point of primary or secondary can be earthed, it is best to connect the primaries in delta.

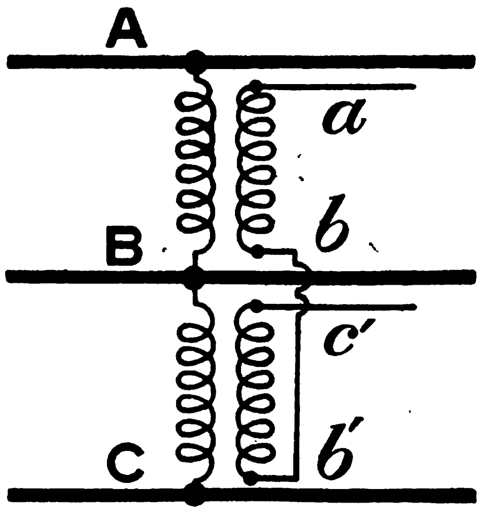


FIG. 205.—Two Pressure Transformers on a Three-phase System.

Current transformers may be combined in a similar manner. For example, on a three-wire polyphase system two transformers can be employed, connected as shown in Fig. 118 (p. 206) (see also Fig. 149, p. 253). Under these conditions if the secondary of the current transformers in line A or B is reversed the resultant current will be in phase with the pressure across AB, so that a single-phase pressure transformer will suffice. Similarly on a four-wire system

[1] R. C. Clinker, *Electrician*, Nov. 10th, 1905, and Jan. 6th, 1906.

the current in the fourth wire is the resultant of the currents in A, B, and C, and may, therefore, be obtained by the use of only three current transformers. This method is of value for detecting earth faults in a three-phase three-wire system earthed at the generating station. Under normal conditions the sum of the currents in the three lines is zero, but on the occurrence of an earth the fault forms a fourth "wire," and the currents in the transformer secondaries no longer have zero resultant, so that an instrument connected at

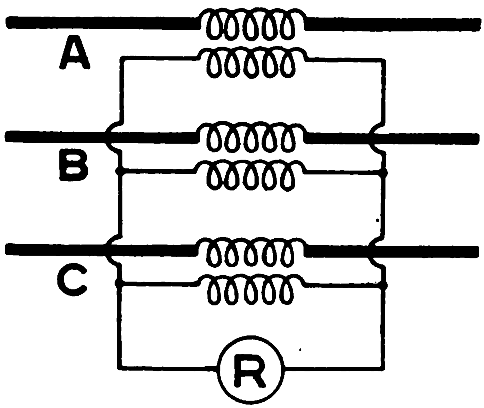


FIG. 206.—Protective Relay Connections on a Three-phase Earthed System.

R (Fig. 206) receives a current proportional to that flowing to earth through the fault.

In connection with poly-phase wattmeters it has been shown that it is sometimes necessary to subdivide the current windings in such a way that each element is supplied from two lines of the system. By the use of current transformers this subdivision of the windings themselves can be avoided, the secondary currents being added as already indicated and the resultant passed through the instrument winding. The connections for a three-phase four-wire wattmeter working off both pressure and current transformers on this principle are given in Fig. 207. This arrangement is equivalent to that of Fig. 120 (p. 208).

It is usual to **immerse transformers in oil or compound** for pressures above, say, 7,000 volts. At such pressures sharp edges or points on the windings are likely to give off an appreciable brush discharge. In air this action produces ozone and nitric acid, which attack any organic insulation and eventually produce breakdown.

The choice of a suitable oil or compound is a matter of great importance. **Transformer oil** may be defined as a pure hydrocarbon free from animal or vegetable oils and

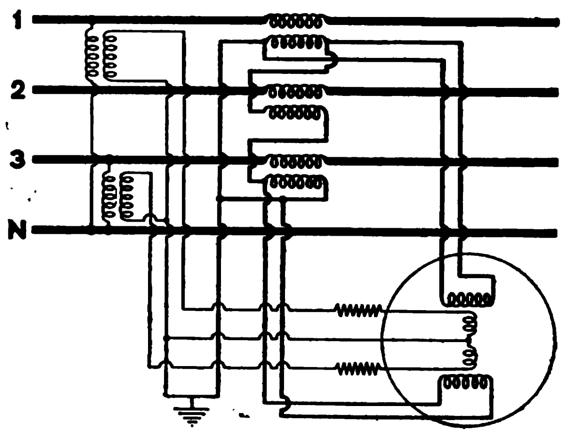


FIG. 207.—Two-element Wattmeter on a Three-phase Four-wire System.

from any substance liable to modify its properties under working conditions. The oil in a transformer has two distinct functions to perform, namely to insulate and to aid in the dissipation of the heat generated.[1]

As regards **dielectric strength,** a good oil should be capable of withstanding 10,000 volts (R.M.S. value) between a needle point and disc $\frac{1}{10}$ in. apart. For a breakdown test $\frac{1}{2}$-in. spheres are often recommended, and the distance for a given pressure will then be increased. The presence of the smallest trace of moisture in the oil lowers the dielectric

[1] See Digby and Mellis, *Journal Inst. E.E.*, Vol. 45, p. 165 (1910); Michie, *Journal Inst. E.E.*, 1910; also report of research committee, *Journal Inst. E.E.*, Vol. 53, p. 146 (1915), and Vol. 54, p. 497 (1916).

strength enormously. For example, 0·02 per cent. of water may lower it by as much as 25 per cent. This forms, in fact, one of the usually accepted methods of testing for the presence of water, and an oil withstanding the above-mentioned breakdown pressure may be assumed to be thoroughly dry.

The presence of moisture further shows itself by a lowering of the **resistance,** and 2,000,000 megohms per cubic centimetre may be regarded as a satisfactory figure for dry oil. The insulation resistance is, actually, more conclusive than the breakdown pressure. The presence of dust in the oil is often even more serious as regards breakdown than that of water.[1]

A further trouble which is experienced with transformer oil is the **formation of sludge** as time goes on. This sludge adheres to windings, etc. and being extremely viscous and a bad conductor of heat, leads to serious overheating. Certain oils (particularly those of Russian origin) are much more satisfactory than others in this respect, but in all, the formation of sludge, which appears to be due to the oxidisation of certain constituents of the oil, is accelerated by high temperature, exposure to the air, and contamination by dust. Moreover, contact with bare copper and some other metals seems to facilitate the formation of sludge, possibly through catalytic action.

With a view to preventing the formation of sludge as well as to avoiding contamination with water, access of air should be restricted as much as possible, and the area of the oil surface exposed to air inside the case should be reduced to a minimum. If this is done, all bare copper well tinned, and the temperature of the oil not raised above, say, 160° F., no trouble should be experienced.

Since the transference of the heat of the windings to the walls of the case is dependent almost entirely upon convection currents, it follows that the less viscous oils (*e.g.* those of American origin) are the best in this respect. The flash-point should not be less than 150° C.

[1] Report No. 25 of Third Section of Electrotechnical Laboratory of Tokyo, *Electrician,* Vol 28, p. 659 (1917).

The **tanks** employed should be large enough to give a clearance of at least 1½ in. all round the transformer and, say, 2 ins. beneath, for pressures up to 10,000 volts. Above this the clearances should be greater. All openings for terminals or filling should be above the level of the oil, so as to obviate leakage, and if the transformer itself is supported from the lid, convenience in assembling is secured. The tanks may be of cast iron or better of pressed or welded sheet steel, and should not be airtight, as there is then a risk of explosion if the transformer is burnt out.[1]

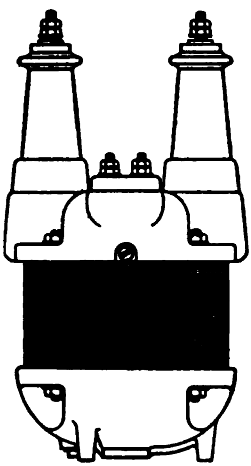


Fig. 208.—Compound Filled Instrument Transformer.

Compound insulation, for which any good "cable compound" will serve, is more cleanly than oil, but is unfortunately a poor heat conductor and, owing to the absence of convection currents, transformers insulated in this way are liable to overheat. The tanks employed are similar to those used for oil, but smaller clearances are permissible.

A compact arrangement of compound insulated transformer is shown in Fig. 208. The shell type core has a cast iron cap bolted on to it at each end, making a tight joint with the laminations. One cap carries the leading in insulators, and the other the feet or holding down lugs. The whole of the interior space is filled with compound which entirely surrounds the windings.

It may be mentioned that in tank type current transformers only one primary insulator is necessary, since both ends of the primary winding can be brought out close together if lightly insulated from each other. This construction, which is shown in Fig. 209, besides reducing magnetic

[1] Attempts to produce a non-inflammable oil have not so far proved successful, although the use of carbon tetrachloride has been attended with some success.

leakage, has the advantage of preventing magnetic interference due to the connecting leads.

Open type transformers should always be protected by insulating varnish. The transformer is first dried *in vacuo* and the varnish run in before reducing to atmospheric pressure, so that the windings are entirely sealed up in varnish or "**impregnated.**"

The following figures may be useful in **specifying instrument transformers**. The accuracy demanded depends largely upon the class of work required; and where limiting figures are given, it is to be assumed that the better performance is representative of testing instruments, while the other represents the poorest performance usually tolerated in switchboard work, and even then rarely met with except at low frequencies.

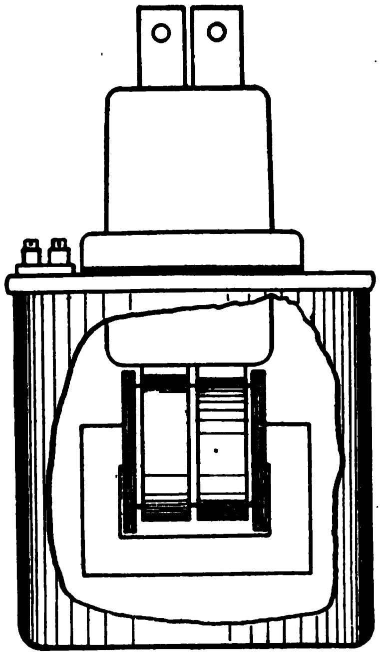


FIG. 209.—Tank Type Current Transformer with Single Primary Insulator.

Pressure transformers :—

(1) The ratio between primary and secondary voltages should be constant within about $\pm$ 0·5 per cent. from 10 per cent. to 130 per cent. of normal voltage with the rated secondary load. Consequently a rise or fall of 10 per cent. in the primary voltage should be without appreciable effect on the ratio.

(2) The secondary voltage should not drop more than 1 per cent. below that on open circuit, when the full rated amperes at 0·8 power factor (lagging current) are taken from the secondary.

(3) The phase difference should not exceed 0·5° to 1·0° at any load less than that defined under (2).

Current transformers :—

(1) The ratio should be correct to within ± 0·5 per cent. to 1·0 per cent. down to one-fifth of rated current and to within 1 per cent. to 2 per cent. from one-fifth to one-tenth of rated current.

(2) The ratio should not be affected by more than 2·0 per cent. by a change of secondary load from short circuit to the full rated secondary volt-amperes when carrying half the rated current.

(3) The phase difference between primary and secondary currents when operating wattmeters, etc., should not exceed 0·5° to 2° at any current between one-tenth and the full current, and with any secondary impedance below the rated maximum.

Determination of Ratio and Phase Displacement in Instrument Transformers.

The accurate testing of current and pressure transformers for ratio and phase is not an easy matter. Various methods have been proposed from time to time, amongst the most satisfactory being the following :—

In the **double wattmeter method** due to Drysdale[1] (see p. 210) the primary current passes through one element and the secondary current through the other. The two are opposed, so that the torque is proportional to the difference between the primary current and the secondary current multiplied by a constant. To measure the phase displacement a condenser is connected in series with the pressure circuit, so as to bring the current in it into quadrature and so give zero reading for zero phase displacement. In order to obviate the use of a wattmeter of which the two elements carry different currents, Murphy employs the secondary of a transformer of known ratio and phase to supply one side of the double wattmeter, while the

[1] *Electrician*, Nov. 16th and 23rd, 1906, and July 29th, 1910.

other side is fed by the secondary of the transformer under test. The two primaries are connected in series.

A simple **potentiometer method** applicable to current transformers is shown in Fig. 210.[1] The primary winding PW is connected in series with a shunt, PS, and the secondary winding SW with another shunt, SS, and a loading resistance, L. Across PS is connected a potentiometer resistance of total value R ohms, while SS is connected through a vibration galvanometer, VG (p. 121), across a

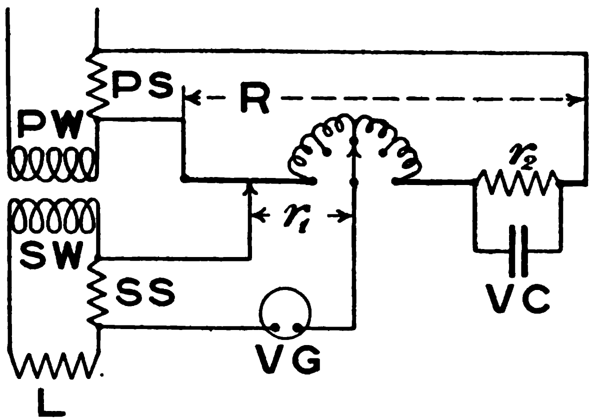


FIG. 210.—Potentiometer Method of Testing Current Transformers.

portion of R having a resistance of r_1 ohms. The vibration galvanometer is brought to zero by adjusting the resistance r_1 and the variable capacity VC. When balance has been attained, the ratio of transformation is—

$$\frac{\text{Primary current}}{\text{Secondary current}} = \frac{\text{resistance of } SS}{\text{resistance of } PS} \times \frac{R}{r_1}.$$

The phase displacement in degrees is—

$$\varphi = \frac{180}{\pi} \cdot \frac{r_2^2\,\omega\,C}{R},$$

where C is the capacity of VC and $\omega = 2\pi \times$ frequency. In the rare event of the secondary current lagging instead

[1] *Elektrotechnische Zeitschrift*, Vol. 36, p. 360 (1915).

of leading—owing, for example, to a very inductive load (see p. 318)—an inductance must be used in place of the capacity. Gifford describes a method of determining phase displacement by means of a phase meter.[1]

An accurate method, employing two wattmeters and an independent source of supply capable of adjustment as regards phase, is described by A. E. Moore,[2] whilst Makower and Wust give a convenient method of determining the phase displacement of a current transformer by means of a phase-shifting transformer.[3]

Graphic or Recording Instruments.

These instruments, which are also called "curve-tracing" instruments, "registering" instruments, and by other ambiguous names, are better spoken of as "graphic" instruments, using a term which originated in America. As an example of the confusion which exists at present, it may be mentioned that watt-hour meters are often loosely spoken of as "recording wattmeters," although actually neither recorders nor wattmeters. The expression **graphic instrument,** or **grapher,** obviates all confusion, and is used throughout the present volume.

In its simplest form a grapher consists of a measuring instrument whose pointer carries at its extremity a pen filled with ink, resting on a paper "chart," which is moved forward by means of a clock. The chart is divided in one direction to represent time and in the other amperes, volts, or other quantity to be measured.

Simple as such an arrangement would appear, the design of a satisfactory instrument is a matter of considerable difficulty. In the first place, owing to the fact that the pen rests upon the paper, the friction is considerable, and, in order to overcome it, the force exerted by the movement has to be increased, often with a corresponding decrease in electrical

[1] *Electrician*, Vol. 77, p. 166 (1915).
[2] *Journal Inst. E.E.*, Vol. 51, p. 346.
[3] "Phase Lag in Current Transformers," *Electrician*, Vol. 79, p. 581 (1917).

accuracy. The **frictional error** in a grapher must be looked at from a somewhat different point of view from that in an ordinary instrument, where it is confined to the pivots, and in which the criterion of satisfactory working is the ratio of torque to weight (see p. 36). In a grapher pivot friction usually forms an insignificant part of the total friction, which is nearly all represented by that of the pen on the paper. The necessary torque is, therefore, almost independent of the weight of the moving parts, and depends upon the travel of the pen point. It is in fact a function of—

$$\frac{\text{Force at pen point for full deflection}}{\text{Chart width}};$$

that is,—

$$\frac{\text{Torque for full deflection}}{\text{Chart width} \times \text{pen-arm length}}.$$

If the torque is measured in gramme-centimetres and lengths in centimetres, this ratio must not in any case be less than 0·05, and should preferably be 0·1 or more. From these considerations it is clear that to specify a certain torque is meaningless in the case of a graphic instrument.

The following may be regarded as the essential parts of all graphers :—

(1) The electrical movement.
(2) The chart on which the curve is traced.
(3) The pen or other tracing mechanism.
(4) The clock or other chart-driving mechanism.

Of the **electrical movement** little need be said. Almost any of the forms already described can be adopted, provided they possess a sufficiently high torque to overcome friction. The **damping** is of importance, since the moving parts are heavy; and if the load is very variable, a wide band of ink is produced which is not only indistinct, but uses up an excessive amount of ink. This is well shown in Fig. 211, the left-hand record being that of a poorly damped instrument and the other that of one which has purposely been rendered sluggish, the chart speed in each case being

1 in. per hour. The usual method of damping consists of an oil bath with paddle or piston.[1] Unless very large, a pneumatic or eddy current damper is not sufficiently powerful to control the heavy moving parts of a graphic instrument.

Charts fall roughly into the following classes: (*a*) sheet charts, usually 12 ins. to 18 ins. long and arranged to clip round a clock-driven drum; (*b*) roll or continuous charts, consisting of strips some 50 ft. or more in length which are put into the grapher in the form of rolls and gradually

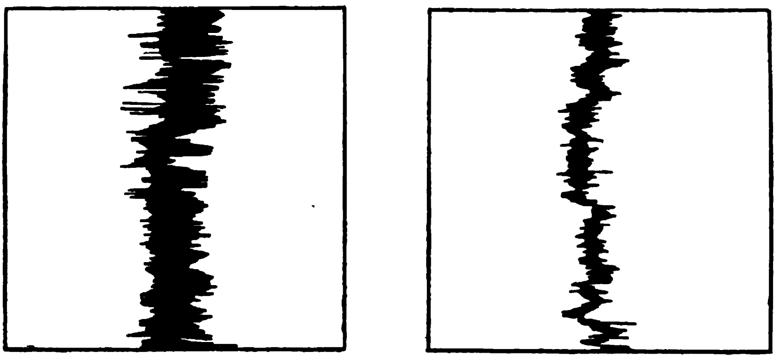


FIG. 211.—Records showing Effect of Damping.

wound off by means of the driving mechanism or clock; and (*c*) circular or "disc" charts, which are rotated round their centres, and have time lines radiating therefrom, as seen in Fig. 212.

Paper is almost invariably used for charts, although other materials, such as smoked glass or celluloid, sensitised or chemically prepared paper, and so forth, have been used for special purposes, but cannot be regarded as a practical proposition.

The paper used must have an extremely hard or "super-calendered" surface, so as to resist penetration by the ink which necessarily, stands on its surface. If the ink is absorbed, not only is the record spoilt, but the supply of ink in the pen

[1] See also p. 43.

is soon exhausted. The chart, of whatever form, should have both time and range divisions and figures printed on it. The hours are occasionally numbered 1 to 24 to distinguish day from night. An independent scale, with or without a pointer, is convenient.

The ordinary grapher has a chart in which the time divisions are curved to a radius equal to the pointer length. There is little or no disadvantage in this, since, even if it is

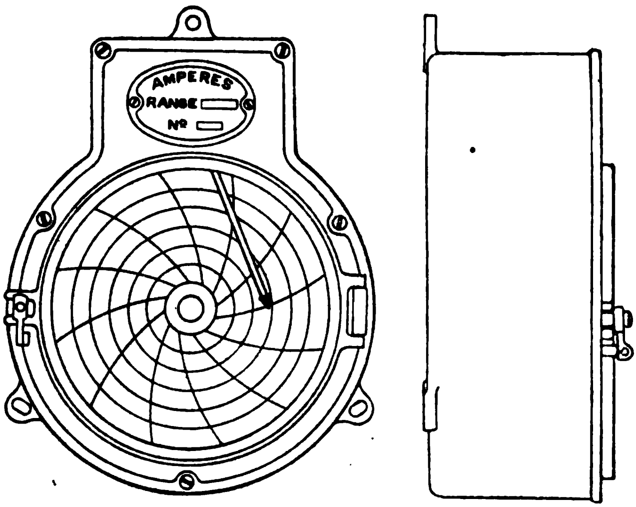


FIG. 212.—Disc Chart Grapher.

wished to "planimeter" the curve, this can be done without appreciable error. At the same time, several instruments have been introduced which take rectangular co-ordinate charts, and so long as this result can be attained without increasing frictional and other errors it may be held to present some advantage (see p. 352).

The usual length of a roll chart is about 60 ft., which is equivalent to a thirty days' run at a speed of 1 in. per hour. The best width of chart depends upon the purpose in view, but 4 ins. may be taken as a very useful width and is that most usually adopted; 3 ins. is too cramped, and 6 ins.

leads to an unnecessarily large instrument and waste of chart.

In measuring the area of a record the ordinary **planimeter** can be used, but the process is laborious, since a long chart must be divided up into short lengths and each one measured separately. To obviate this, special forms of planimeter have been devised which are so arranged that an unlimited length of chart can be drawn under the measuring wheel, it being merely necessary to keep the pointer on the curve as the record passes under it. It is not necessary with these planimeters to travel back along the base line, as is the case with the ordinary Amsler pattern. They are made in two forms, differing but slightly in principle, according to whether the charts in question have rectilinear or curved time lines.

As regards the **inking mechanism,** the usual arrangement consists of a small receptacle or pen fixed to the end of an arm carried by the spindle of the electrical movement. These pens take various forms, some of which are shown in Fig. 213.

a is the "spoon" or V pattern with open top, easy to fill, but liable to dry up and, in the case of violent movements of the pen-arm, to spill. *b* is a much-improved pen of the same class. It is entirely closed on three sides, and partially so at each end. It has the advantage of being easily filled and yet of retaining the ink satisfactorily. *c* is one form of "bucket" pen—the Dittmar. The fine tube leading to the bottom is liable to clog, particularly if allowed to stand idle, and is better replaced by an open capillary space, as shown at *d*. This pen (Everett-Edgcumbe) consists of two parts, the bucket and the removable ink conveyer, which is seen by itself in the upper part of the figure and also in the lower sectional plan. A great advantage of this arrangement lies in the ease with which the inner part can be removed for cleaning, without fear of damaging it. *e* is the Murday pattern, constructed on the lines of a drawing pen. *f* is a conical pen, employed to some extent on the Continent and often provided with a "bristle" in

the orifice, like a stylographic pen. At *g* is shown an arrangement due originally to A. P. Trotter, which can be used with fair success in cases where a very large supply of ink is essential, owing to high chart speeds or very variable loads. It consists of a trough of ink running across the chart, into which dips a fine capillary tube bent into a "swan-neck."

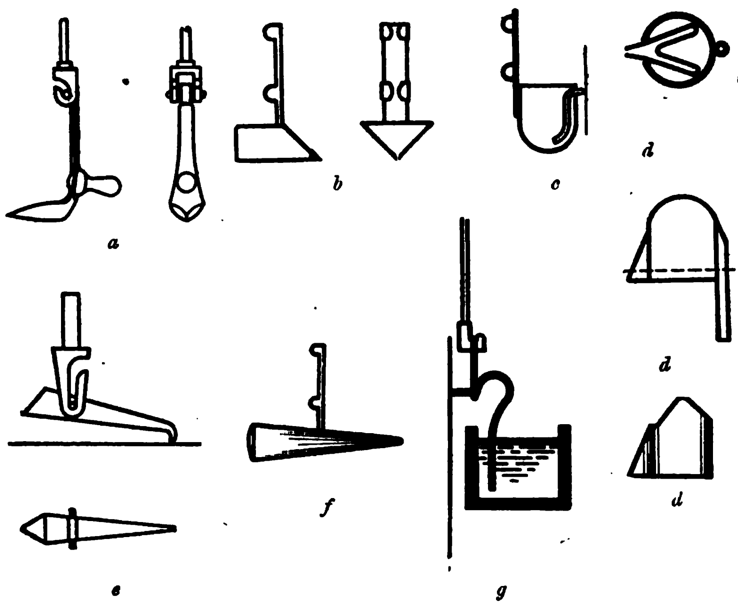


FIG. 213.—Grapher Pens.

The tube is liable to clog and the ink in the trough to become thick and accumulate dust, but when well looked after it affords a simple means of ensuring an ample supply of ink. In Fig. 214 is shown the pen of the "inkwell" grapher (see p. 347), which fulfils the same purpose in a more satisfactory manner.

In a general way it may be said that the simple enclosed V pattern (*b*) and the improved bucket pattern (*d*) are the most satisfactory and meet almost all requirements, except when a very large supply of ink is essential. In this case

not only is an extra-large pen unsatisfactory (as increasing the moment of inertia of the system and the pressure on the jewels), but the varying weight of the ink in the pen as it is gradually used up may make a difference in the reading at either end of the scale of as much as $\frac{1}{10}$ in.

The satisfactory operation of a grapher depends more upon the care taken with the pen or other inking arrangement than almost anything else. The pen is necessarily a delicate piece of mechanism; and if the writing point once

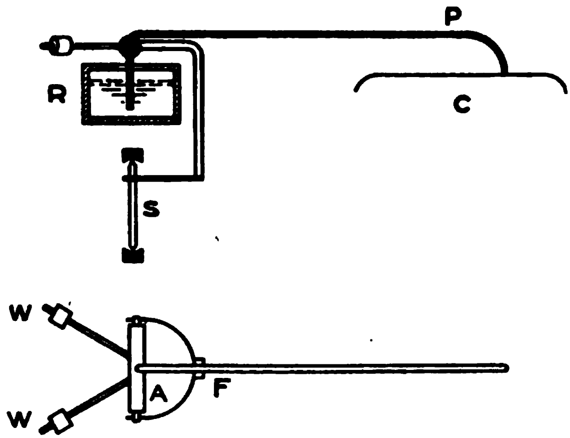


FIG. 214.—Inking System of "Inkwell" Grapher.

becomes bent or opened out, it is not easy to remedy the defect, so that in most cases it is best to replace it by a new one.

If a pen is allowed to stand idle for a long time, the ink will dry up and very probably clog the point. It can be cleaned out with methylated spirit or even warm water, a fountain-pen "filler" being a useful adjunct. It is always advisable, however, when a grapher has to stand idle for any length of time, to wash out the pen. Filling it with a little glycerine makes subsequent inking an easier matter, particularly in the case of capillary pens.

The **pen-arm** and the method of attaching the pen to it, are matters of considerable importance. The pen must be

easily removable for cleaning or replacement, and both the pen and its clip must be incorrodible. A certain amount of flexibility is essential in the arm in order that a light and constant pressure may be exerted between pen and paper. This may be secured by hinging either the arm or the pen (see Fig. 213, *a*) or, better, by the use of a flexible pen-arm, as is done in the case of the Everett-Edgcumbe graphic instruments. The latter alternative has the great advantage of preventing damage to the arm through its getting bent and thereby altering the balance of the movement and the pressure on the chart. Whichever scheme is adopted, a milled head adjuster should be provided in order that the pressure on the paper may be set to give satisfactory marking with minimum friction, since, upon this the efficient working of the instrument so largely depends.

In what has been said the ordinary direct acting form of grapher has, chiefly, been considered. In the case of relay graphers (see p. 359) the size and weight of the pen is of small consequence, and in the inkless grapher (see p. 355) the pen is dispensed with altogether. In a recently introduced model, the **inkwell grapher** (Everett-Edgcumbe), the question of an adequate ink supply has been attacked in a different manner, which may conveniently be described here.

The main idea is to employ a central reservoir, concentric with the spindle of the movement. The inking arrangements are shown in outline in Fig. 214. The spindle S is fixed to the electrical movement, moving coil, moving iron, or dynamometer, as the case may be. At its upper end it carries a cranked fork, F, in which is pivoted a cross-arm, A, carrying the pen P. This portion is shown in plan also. The pen itself consists of a capillary tube, one end of which dips into a fixed ink reservoir, R, holding sufficient ink for a month's run, the top being nearly closed to prevent evaporation and to keep out dust. The counterweights WW are so adjusted that the marking end of the pen P rests on the chart C with just sufficient pressure to ensure satisfactory marking, as the ink siphons along the tubular pen. An

oil-damper (not shown) is provided to render it dead-beat under sudden changes of load.

Besides the advantage of an almost unlimited supply, the accuracy is quite unaffected by the level of the ink in the reservoir. Moreover, the pivots being vertical, friction and wear are reduced to a minimum. As the electrical movement is behind the chart-driving clock, the space occupied on the switchboard is unusually small. If it is wished to leave one of these graphers without attention for more than eight days at a time, the clock can be arranged for electrical winding. The chart itself lasts for a month at a speed of 1 in. per hour, so that no attention is then required during that time.

In the majority of cases the **chart-driving mechanism** takes the form of a **clock** with balance wheel escapement or, more rarely, a pendulum. For graphers taking sheet charts the clock has often to be wound every twenty-four hours, whereas for roll charts an eight-day clock should be fitted for all ordinary chart speeds. Thirty-day clocks are occasionally provided, but are usually lacking in power and, unless under very exceptional circumstances, are unnecessary. The unrolling and passing through of the chart requires a fairly large torque ; and, as the friction is variable, a very robust and powerful wheel train is essential to prevent damage to the escapement through overswinging (or "banking," as it is called). In order to avoid winding up the clock spring by hand, electrical winding arrangements are often provided in which, by means of a contact every few minutes or every few hours, the driving spring is kept under tension.

Another method of driving the chart which has been developed by some makers consists in an **electric motor** acting through a worm or other reduction gear, the speed being automatically kept constant. Fig. 215 shows, diagrammatically, one form of this arrangement. To the armature of the series-wound driving motor is attached a centrifugal governor, shown at G. When the speed of rotation exceeds a predetermined amount contact is made,

and the resistances RR form a shunt to the armature. In this way the speed is reduced sufficiently to cause the contacts to open, and the operation repeats itself. In practice the contacts touch just sufficiently to keep the speed steady. These contacts are usually of platinum, iridium or tungsten, and are permanently bridged by a com-

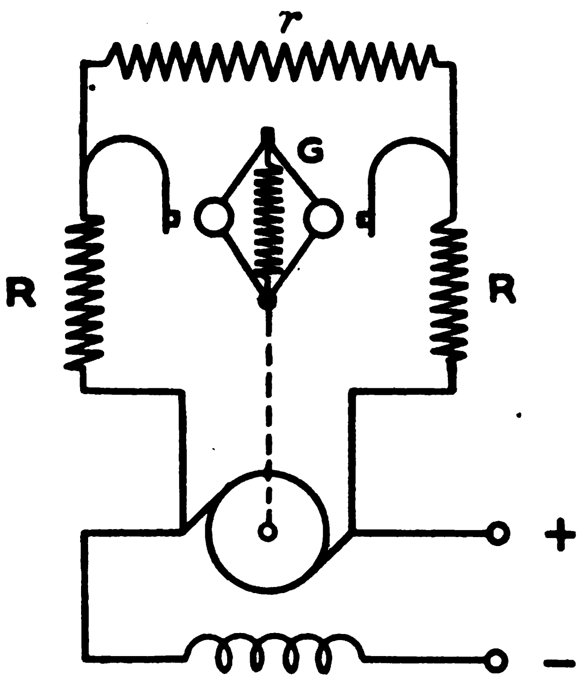


FIG. 215.—Electric Motor Chart-driving Mechanism.

paratively high resistance, *r*, which reduces sparking to a minimum. The accuracy of timing which is possible with such a device is quite sufficient to meet ordinary requirements.

Various devices are in use for **driving the chart.** In some instruments friction alone is relied upon, the chart passing round a rotating roller. Another arrangement is to mill teeth in the centre of this driving roller. Needle points

are occasionally inserted in the periphery of the driving wheel, but they throw an additional load on the clock and are apt to tear the paper. Where a positive drive is desirable, as, for example, in the synchronised grapher (see p. 355), the chart can be perforated along one or both edges with holes into which pins projecting from the driving wheel are caused to engage.

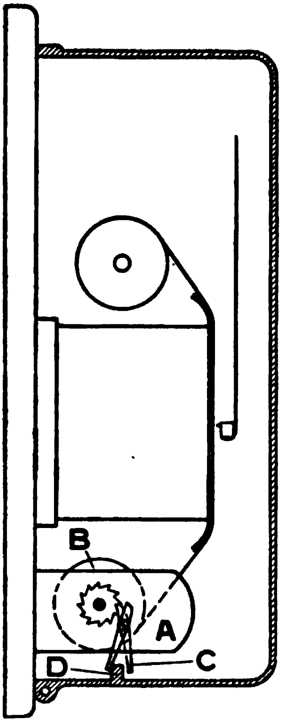


FIG. 216.—Automatic Chart Receiving Spool.

In the case of roll charts some provision must be made for **disposing of the chart after it has received the record.** A short length — say, one or two days' supply — can be allowed to coil itself up in the case, but when this is not sufficient a slit is often cut in the bottom of the case through which the chart can pass either into a receptacle or on to a spool provided with a handle for winding it up. Sometimes a weight is attached to the chart as it passes out of the case, the pull assisting the clock spring. The weight must be correctly proportioned, as if it is too great the escapement will "bank," and the clock will be damaged.

The best arrangement consists in a spring-wound roller contained in the lower part of the case, and as fitted by Everett-Edgcumbe is shown in Fig. 216. In the oblong box A a spring is enclosed, which drives the roller, B, receiving the chart after passing under the recording pen. The pawl C is so arranged that when in the position shown by the dotted lines the spring is clamped. On the cover of the instrument is a projection, D, which engages with the pawl and lifts it off the teeth into the position shown by the full lines directly the case is closed. By this means

the roller is clamped so long as the case is open, and the chart can be attached or removed, but is freed directly the case is closed. In this way the chart is drawn taut and wound up as fast as it is passed through by the timing mechanism. The auxiliary spring, moreover, serves the useful purpose of relieving this mechanism of part of the work of driving the chart, and thus facilitates good time-keeping.

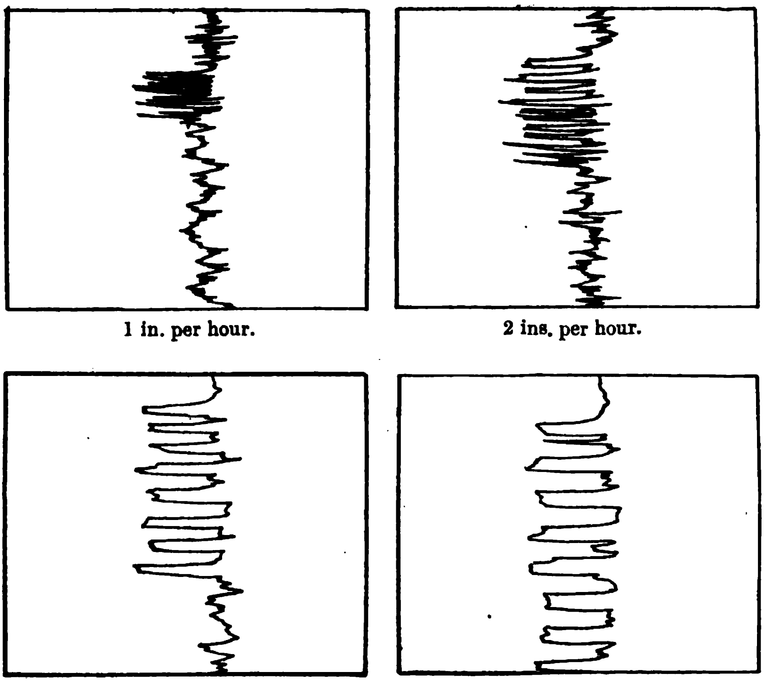
In some instruments the receiving spool is rotated by the clock itself (see Fig. 224, for example), and in that case, owing to the varying diameter as layer after layer is wound on to it, a certain amount of slip has to be arranged for, and this makes considerable demands upon the clock as regards driving force.

Where space is restricted, a circular chart is often valuable. Fig. 212 shows the "**disc**" **pattern** of Everett-Edgcumbe, in which the chart consists of a disc which rotates once in twenty-four hours or twelve hours, as preferred. The hours are marked round the circumference, and the circular divisions represent the quantity to be measured (volts, amperes, etc.). The scale is 2½ ins. wide, and the entire record is visible. Besides the saving in space which is possible with such a grapher, its first cost is considerably lower than that of the ordinary pattern. A disadvantage lies in the limited chart speeds available, namely ½ in. or 1 in. per hour at the mean radius of the chart, and in the peculiar form of the time divisions.

The **best chart speed** for a grapher depends entirely upon the requirements of each particular case. If the quantity to be measured varies but slowly, a low speed (say ½ in. per hour) is best. If it is varying rapidly, speeds up to as much as 12 ins. per minute can be used to advantage. Fig. 217 gives, side by side, sections from a number of records dealing with much the same load, but with chart speeds of 1 in., 2 ins., 6 ins., and 12 ins. per hour respectively. This affords a good idea of the advantages of a high chart speed under such conditions. In cases where still higher speeds, up to, say, 12 ins. per minute, are required, the

clock escapement is replaced by some form of centrifugal governor.

As has already been mentioned, a preference is sometimes expressed for an instrument in which the pen moves in a straight line instead of in a circle, in order that the charts



1 in. per hour. 2 ins. per hour.

6 ins. per hour. 12 ins. per hour.

FIG. 217.—Records at various Chart Speeds.

may have **rectangular co-ordinates.** Whether the advantage gained is worth the increased frictional error, which is inevitable with most of these devices, seems doubtful, but the following arrangements may be mentioned as having been used by different makers.

In Fig. 218 M_1 and M_2 represent the spindles of two electrical movements, moving coil, dynamometer, moving iron, etc., as the case may be, connected in series or

parallel. Each carries a light aluminium wheel with grooved rim, round which passes a very flexible wire C.C. The lower portion of this wire drives the pen P, attached to a rod resting on rollers, RR. As the movements deflect, the pen is driven across the chart in a straight line. An air

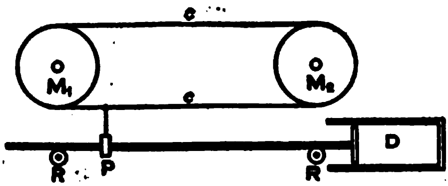


FIG. 218.—Double Element Grapher.

dashpot, D, damps out the swings to some extent; but, owing to the mass of the moving parts, it is far from dead-beat in its action, and the friction is excessive unless a large amount of power is absorbed.

This arrangement has advantages when it is wished to obtain on a single record the sum of two quantities, as in

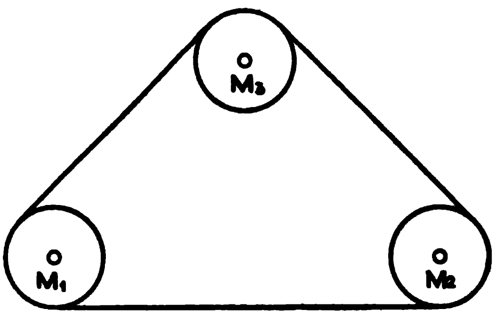


FIG. 219.—Triple Element Grapher.

measuring the total power in a three-wire three-phase system by means of two wattmeters (see p. 202). Or, again, as shown in Fig. 219, it is readily modified so as to record the sum of the torques of three movements, M_1, M_2, and M_3, as required in the case of a four-wire three-phase system.

A simple device is shown in Fig. 220, in which D represents the chart-carrying drum, rotated by clockwork, M the move-

ment spindle, and P the pen. The pen-arm is hinged to the pointer at H, and presses against the chart by its own weight. As M rotates H travels in the arc of a circle round it as centre, but the pen P moves across the chart in a straight line.

A straight line link motion is illustrated in Figs. 226 and 227, as applied to relay instruments.

The pen shown at *e* in Fig. 213 represents another method (due to Murday) of obtaining rectangular co-ordinates. The point of the pen is made slightly heavier than the other

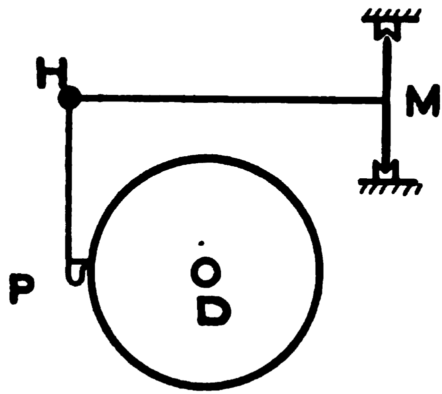


FIG. 220.—Simple Rectangular Co-ordinate Device.

end, so that as the pen-arm swings across the chart the point always rests upon the paper and traces a straight line.

Yet another variation is shown in Fig. 221. The chart, after leaving the roll A, is bent round the curved guide B, whence it passes on to the lower roller C. The pen P is carried by the cranked arm D, which is rigidly attached to the movement spindle E. The latter is pivoted at the centre of the circle of which B forms part of the circumference. As the movement deflects the pen P travels in a circle with E as centre, and so traces a straight line on the chart, against which it is gently pressed.

In order to **eliminate pen friction,** two courses are open. The one is to **keep the pen-arm clear of the paper,** and the

other is to move the pen by means of a relay so that any friction it may encounter does not affect the accuracy.

The earliest device of the former kind was the so-called "syphon telegraph recorder" of Kelvin, in which the ink flowed down a capillary glass tube travelling almost out of contact with the paper. By means of a trembler the whole was kept in vibration, and this served both to reduce friction and to accelerate the flow of ink. In the "spark recorder" of Siemens the spark from an induction coil or mercury interrupter passes from the pointer tip through the paper chart, burning a small hole as it does so. By this means a continuous trace is obtained without any friction. The disadvantages of this arrangement are that the curves are not very clear; and that the paper must be thin and the chart speed high, or it will be burnt through. Besides this, the battery and continuously running coil or interrupter require a certain amount of attention.

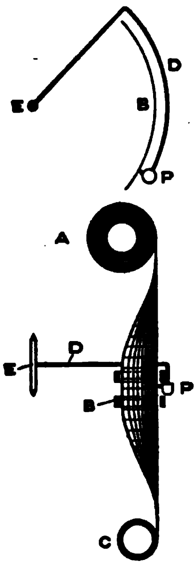


FIG. 221. — Bent Chart Rectangular Co-ordinate Device.

Another and more universally applicable arrangement consists in keeping the pen-arm clear of the chart, depressing it at intervals into contact with it. One well-known form is the Everett-Edgcumbe **inkless synchronised graphic instrument.** In this not only is ink eliminated, as well as all friction between pen and paper, but any number of instruments, on a switchboard for example, can be worked from a single controlling clock, and all being electrically interlocked they work absolutely synchronously as regards chart-timing.

Fig. 222 shows the general arrangement of the circuit when a battery (B) is used to actuate the system. At fixed intervals, usually every five seconds, the controlling clock CC closes the circuit for a fraction of a second. The current flows in series through the chart-driving magnet CM and

the tapping magnet TM. The former moves the chart forward by a definite amount, and the latter makes the record in the way described later.

The **controlling clock** which sends these impulses is shown in Fig. 223. The pendulum P, of which for simplicity only the upper part is shown, makes two half-swings per second; that is to say, it travels once from right to left in every second. In so doing, the pawl A moves the toothed wheel W, on which it rests lightly, forward one tooth per second. The teeth are so shaped that the pawl in moving from side to side normally passes just under the lower end of the upright C, which is pivoted at B. But every fifth

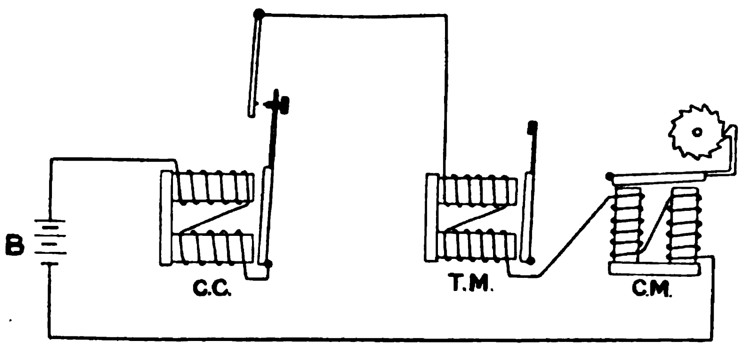


FIG. 222.—Inkless Synchronised Grapher Connections.

tooth is shallower than the rest, so that A engages with the lower end of C and pushes it clear of the projection D. As a result the arm E, which is pivoted at F, falls by its own weight.

At right angles to E is an arm carrying a flat spring, G, at its extremity; and the arrangement is such that when E falls G presses on the pendulum, whereas when E is supported by C the pendulum does not touch it. The force exerted by G, due to the weight M carried by E, provides the driving force necessary to keep the pendulum swinging. Each time E is released, and just before the pendulum comes to the end of its stroke, the arm carrying G, which follows the pendulum, makes contact with the platinum-tipped screw

H and thus, as shown in Fig. 222, closes the battery circuit. The working current flows through the coils KK (CC in Fig. 222), which are thereby energised and attract the

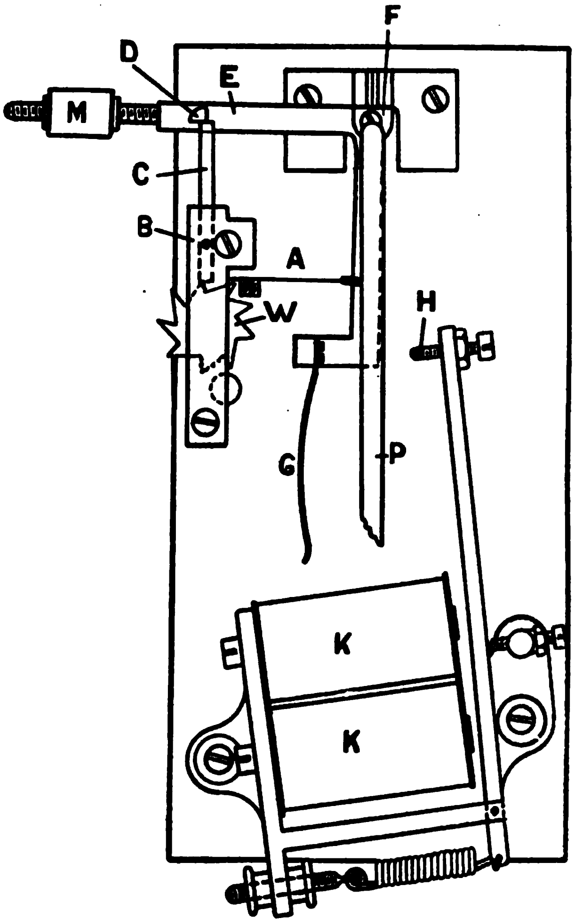


FIG. 223.—Controlling Clock of Inkless Grapher.

armature carrying the contact H. The impulse due to this attraction is sufficient to throw E up again, and the support C, which is pressed against D with a light spring, holds it there, so that the cycle of operations repeats itself, the clock being thus self-winding.

This timing device, which is due to Mr. Hope-Jones and forms the basis of his well-known "synchronome" system of electric clocks, may appear complicated, but in reality the simplicity is remarkable, and the contacts, being rubbed together with considerable force, keep themselves clean and require no attention. For portable use the pendulum is replaced by a balance wheel, and some other modifications are made to eliminate the effects of gravity.

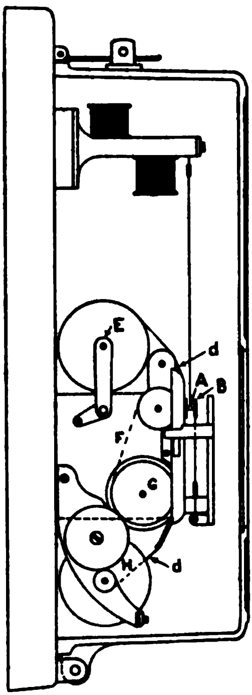


FIG. 224. — Inkless Synchronised Switch-board Grapher.

The **instrument itself** (Fig. 224) consists of a moving coil, moving iron, or dynamometer pattern movement, according to circumstances. That illustrated in Fig. 224 is of the astatic "universal" type, described on p. 142. At the end of the pen-arm is a steel ball, A, which swings freely between the tapping bar B and a typewriter ribbon. An electro-magnet (not shown in Fig. 224, but seen at TM in Fig. 222) attracts B and presses it on to the point A, which in its turn makes a dot on the chart (*d*) through the typewriter ribbon. This dot occurs exactly under A, wherever it may be at the moment, and as the pointer is perfectly free, except at the instant of depression, the accuracy depends simply on that of the movement and is almost as great as that of an indicating instrument.

The chart (*d*), which takes the form of a roll 60 ft. long, is placed between centres at E (Fig. 224). It is provided along one side with a number of holes into which pins carried by the rim of the wheel G, are caused to engage. This wheel is moved through a definite angle by the electro-magnet CM each time the momentary current flows, as shown in Fig. 222.

After passing under the marking point, the chart is wound up on the spool H, from which it can be removed as required.

It will thus be seen that, apart from the increased accuracy attainable through doing away with the pen, the whole system is entirely automatic, and so long as the charts are replaced once a month, no attention whatever is required. When there are **several instruments** in an installation, they can all be **run from one controlling clock** by being connected in series with one another, with the advantage that the timing of all the charts is absolutely identical. This will be the case even if the chart speeds of the individual recorders are made to differ, some being, perhaps, arranged for a speed of 1 in. and others for one of 6 ins. per hour.

When the load is very variable, a record every second instead of every five seconds is often preferable, and can easily be arranged. In this case contact is made at H (Fig. 223) at each stroke of the pendulum, instead of at every fifth stroke.

When more convenient, instead of the battery B a resistance can be connected across the mains and the required current obtained by tapping across a portion of it.

The instrument as described gives curved time lines, but by means of a simple device it can be adapted to give **rectangular co-ordinates.** The pointer, instead of the steel ball A, carries a steel knife edge, which is pressed by the tapping bar B through the typewriter ribbon against a bar fixed under the chart and at right angles to it. In this way all the record points always lie over the bar and therefore in a straight line.

The **Murday "thread recorder"** is based upon the same principle, except that in place of the typewriter ribbon and bar an inked thread is used, the pointer being depressed against it by the clock. Owing to the fact that the tapper is depressed by the clockwork itself and cannot therefore give very frequent taps, it is only suitable for recording a slowly changing quantity, such as temperature.

One of the earliest forms of **relay grapher** was that due to **Callendar,** which is much used in scientific work,

although it has proved too delicate for industrial purposes. In one form, it is adapted to a Wheatstone bridge and records resistance, the working being as follows: Across the chart is stretched the slide-wire of a Wheatstone bridge, and the travelling contact carries a pen which traces a line. The contact, and with it the pen, is pulled along by means of a double clockwork arrangement which winds an endless cord in one direction or the other by means of two relays. The pointer of the bridge galvanometer, when at zero, lies midway between two contacts, but so soon as the balance of resistance is disturbed it deflects in one direction or the other and thereby makes contact and actuates one of the relays just mentioned. This relay in its turn couples the clockwork on to the endless cord, so that the contact is drawn along until balance is restored. The pen meantime traces an accurate record of the position of the contact on the slide-wire and consequently of the resistance. This grapher is also available as a potentiometer, and, in fact, for any zero method using a slide-wire, so long as the quantity to be recorded varies slowly and in accordance with a predetermined law connecting it with the contact position.

Another zero type grapher of the relay pattern is that of **Leeds**. The underlying principle may be gathered from Fig. 225, although the actual apparatus is somewhat complicated. Two "bell-crank" levers, C, are pivoted at FF; and if either of these has the upper arm of the crank raised, the pin D is pushed round the centre E. The pointer of the galvanometer is shown at A, and is pushed upwards at definite intervals by means of the small plate B. When the galvanometer is in the position for zero current it is so set as to rise and fall in the space between the two levers C, as shown in the left-hand figure. If, however, it deflects to the right, the plate B presses it against the right-hand lever, which is thereby turned round, as shown in the right-hand figure. The arm which carries the pin D is periodically forced back into the vertical position, and during this travel is geared on to the pen-traversing mechanism, which is itself attached to the slide-wire contact, so that the latter

is moved along step by step until equilibrium is once more restored, and the galvanometer returns to its central or zero position. The periodic movements of B and E are carried out by means of a small electro-motor, which also drives the chart. This motor has its speed regulated in much the same way as that shown in Fig. 215.

The uses to which such zero instruments can be applied are necessarily limited, and a number of relay graphers of the deflectional type have been introduced. Fig. 226 shows

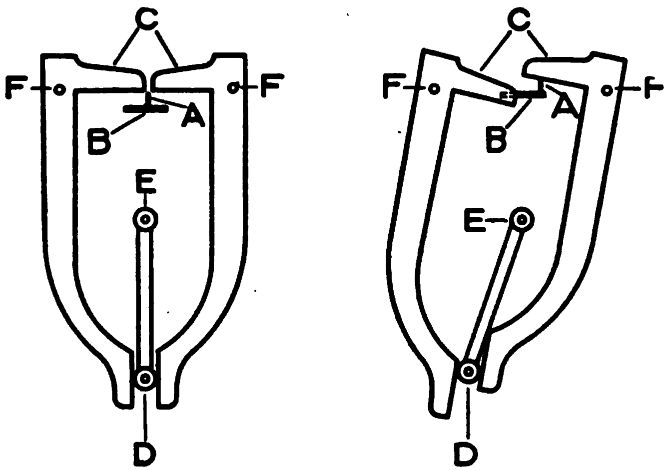


Fig. 225.—Principle of the Leeds Relay Grapher.

one of American origin (**Westinghouse**). The arm carrying the pen P has a roller, C, at its upper end, running between vertical guides, and is itself pivoted at A to the lever B, which is carried by the rocker R. This latter is pivoted at G, and carries at each end an iron core, which is attracted by the solenoids S_1, S_2. The electrical movement illustrated is of the dynamometer type, and resembles the Kelvin balance. It swings between two contact screws; and if, for example, it touches against the upper contact, the solenoid S_2 is excited and draws down the right-hand iron plunger, the travel being retarded by the oil dashpot D. As the rocker R turns round the fixed pivot G, the pen P is drawn

across the chart from left to right, approximately in a straight line. At the same time the spring E is extended and tends to pull the contacts apart. The greater the force with which the contacts are pressed together (which in its turn depends upon the magnitude of the quantity

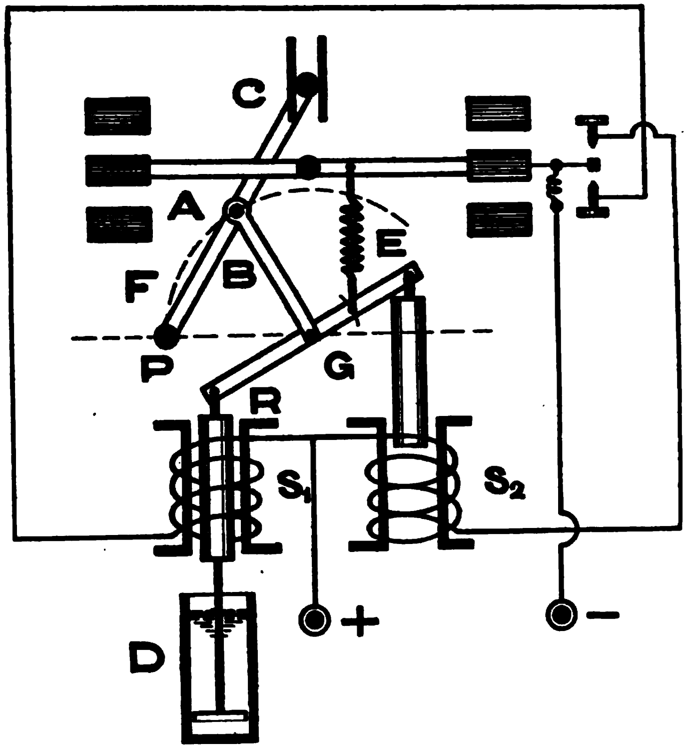


FIG. 226.—Westinghouse Relay Grapher.

measured) the larger the angle through which R must turn in order to put sufficient tension on the spring E to separate the contacts. In this way, therefore, the deflection of the pen is approximately proportional to the torque exerted by the movement.

It is not always possible to control a movement by means of a spring, for example in the case of the ohmmeter or the

phase meter in which the control is electrical and not mechanical. To meet such cases the modification shown in Fig. 227 has been introduced. The pen-arm and rocker are unchanged; but instead of the latter extending a spring, the arm B carries a pin, F, which engages in a slot in an arm, G, pivoted concentrically with the electrical movement and carrying two contact screws. The pointer is fitted with a contact which touches either the one or the other, according to its direction of deflection. Suppose, for example, that contact is made to the right, this excites the right-hand solenoid, and so moves the whole system towards the right. Eventually a point is reached at which equilibrium is restored and the contact is broken, the system coming to rest until contact is again made owing to a change of deflection either in the same or the reverse direction.

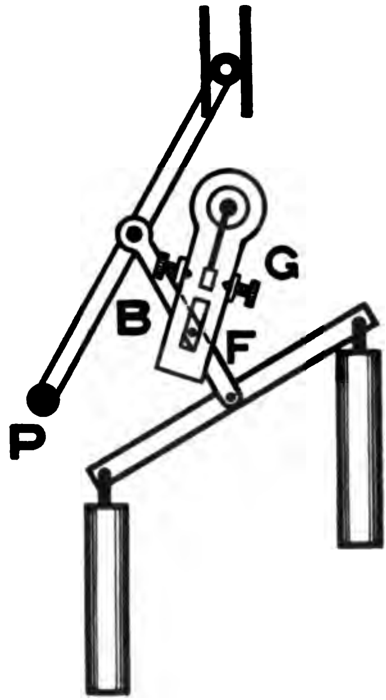


FIG. 227.—Westinghouse Relay Grapher.

An advantage possessed by all relay graphers is that a heavy pen can be carried, giving an unlimited supply of ink. Moreover, errors due to friction between pen and paper are eliminated. A disadvantage lies in their sluggishness in following fluctuations. For example, the pen takes some twenty seconds to travel across the chart from one side to the other under the most favourable circumstances.

Various combinations in which two or even three movements record on the same chart are sometimes of use. A

combined graphic voltmeter and ammeter, known as a "**feeder log,**" consists of two elements fixed side by side, the one recording the pressure and the other the current in a feeder. Where it is of importance that a number of charts should all run exactly in synchronism with one another, two or more instruments are sometimes set up side by side and a common spindle passed through all the clocks. A much better arrangement, however, is to apply synchronised timing as described on p. 359.

For **portable use** almost any of the graphers described can be fitted into a wooden case, preferably with leather carrying handle and rubber feet, to prevent damage if roughly set down. As such instruments are often left unattended for long periods, a roll chart and a large supply of ink are requisite, and some form of chart rolling up gear (see p. 350) is important.

For use **under conditions of excessive vibration,** such as in railway coaches or on tramcars, a spring suspension is advisable. It may be mentioned in this connection that for the purpose of taking records of experimental runs in railway coaches the chart is often driven from the vehicle wheels instead of by a clock, and time marks are made on it at given intervals by a timing device, such as that illustrated in Fig. 223.

The vibrating reed principle (p. 264) does not lend itself particularly well to the construction of a **graphic frequency meter,** although one has been designed on this principle with partial success. A better device is that due to Coleman and described on p. 260. Another arrangement consists of an alternating current motor direct coupled to a continuous current magneto-generator, such as that described on p. 365, and to which a graphic voltmeter is connected. Theoretically a synchronous motor should be used for this purpose, but is seldom admissible owing to the difficulty of starting, and in practice it is found that a squirrel cage motor, provided it is of ample size, is quite satisfactory. The slip is small, and is, moreover, practically constant, so that it can be allowed for in calibration.

Electrical Speed Indicators.

These instruments have come into fairly extensive use, particularly where transmission of speed to a distance is entailed. In its simplest form the electrical speed indicator consists of a magneto-generator or "transmitter" direct coupled or belted to the shaft whose speed is to be measured. The generator may give an alternating or, more commonly, a continuous current. The voltage generated is nearly proportional to the speed, and a voltmeter connected to it can be graduated in revolutions per minute.

An alternating current generator has the advantage that it can either be constructed on the inductor principle, or the magnets can be revolved, so that no slip-rings or sliding contacts are necessary. Unfortunately, an alternating current voltmeter, whether of the induction, moving iron, hot wire, or other type, has a scale which is very much closed up at the lower end instead of being evenly divided throughout. Moreover, the power consumption of such instruments is very much greater than that of the moving coil, so that the generator has to be larger and the connecting leads of heavier section. The continuous current arrangement enables speed in two directions (*e.g.* "ahead" and "astern"), to be distinguished by deflections to the right and left of a central or displaced zero, which is often a valuable feature.

Fig. 228 shows a form of continuous current **transmitter** suitable for use in damp situations, such as on board ship. The whole is enclosed in a waterproof case, glands being provided for the leads. The grooved pulley A is belted or otherwise driven from the spindle whose speed is to be measured, and this in its turn drives the magneto-spindle B through the gear wheels C and D. Carbon brushes are used to collect the current; and as all spindles run in ball bearings, practically no attention is required.

Fig. 229 shows a convenient form of alternating current transmitter without rubbing contacts. The central armature A is fixed, and carries three windings connected in series. The three permanent magnets M are held in position by means of

a ring and bolts inside the drum B, which runs in ball bearings and carries a flat or grooved pulley for driving it.

As regards the drive for transmitters, the most accurate method is clearly a direct coupling, and for this purpose a short length of spiral spring forms a convenient arrangement, as it allows for any want of alignment which there may be. If a pulley is used, a flat webbing belt is the best, and a more exact determination of the diameter of the pulley is

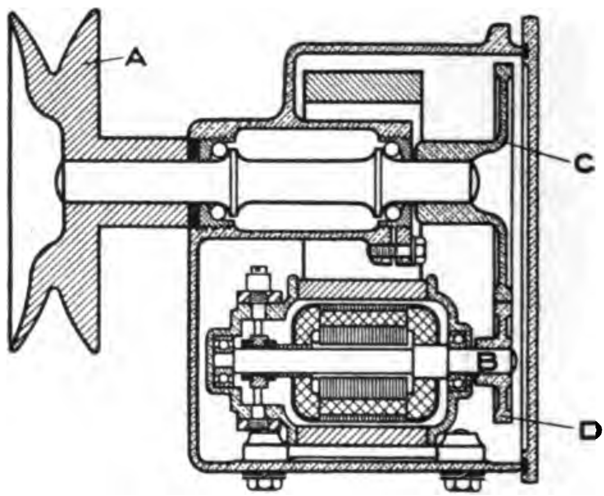


FIG. 228.—Watertight Speed-indicator Transmitter.

possible than with a V groove, although the latter fitted with a spiral wire belt is extremely convenient and quite accurate enough for most purposes. With any form of belt drive there is always a certain amount of slip or creep, but this need not exceed one or two parts in a thousand if care is taken.

The **indicator** is usually graduated direct in revolutions per minute, miles per hour, &c., and is of any form, such as round, sector, or edgewise. For use on board ship it is usually fitted in a watertight case (see p. 20), and, as has been said, if of the moving coil type, may be provided with a central or displaced zero so as to show speeds "ahead" and "astern."

In the case of an alternating current transmitter, direction cannot be indicated in this way, and if it is essential to show it, recourse must be had to a two-phase winding connected to the indicator by three wires. A pivoted metal disc can be caused to deflect one way or the other according to the direction of rotation of the transmitter on the same principle as the phase rotation indicator described on p. 256.

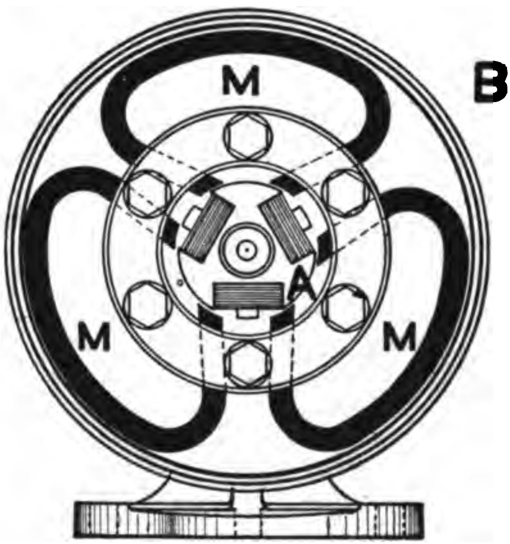


Fig. 229.—Alternating Current Speed-indicator Transmitter.

Fig. 230 shows a special form of indicator for use with an alternating current transmitter, consisting of a moving iron voltmeter with a vibrating reed frequency indicator, in the same case, each being scaled in speeds. The transmitter consists of an alternating current generator, and, while the moving iron instrument indicates the approximate speed throughout its range (0 to 500 revolutions per minute), the vibrating reeds show it with considerable precision at and about the normal (400 revolutions).

In all cases the voltmeter must be empirically scaled, since, owing to the demagnetising effect of the armature current

on the field magnets, the terminal P.D. is not strictly proportional to the speed, the departure from proportionality being greater the larger the load taken from the generator.

Sometimes, and more particularly when sufficient power is not available for driving a magneto-generator, a **simple contact-maker** is attached to the spindle, so arranged as to give a certain number of " makes and breaks " per revolution. A source of continuous current at suitable voltage is connected through it to the frequency indicator, which thus

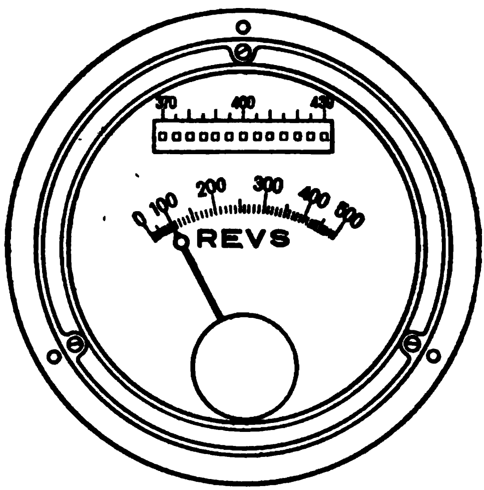


FIG. 230.—Alternating Current Speed-indicator.

receives an intermittent current at a frequency proportional to the speed to be determined. For example, if there are n contacts round the contact-maker (so that the circuit is closed and opened n times per revolution), and if the reed marked " p cycles per second " is set in vibration, the speed is $\frac{120\,p}{n}$ revolutions per minute. As a rule, however, the dial is scaled direct in speed.

A similar arrangement is available for measuring the **slip of an induction motor.** A contact-maker such as that described, making n contacts per revolution—if the motor

has n poles—is driven from the motor spindle. The frequency of supply is first measured—say 50, and then that derived from the contact-maker—say 48·2. The slip is then 1·8 cycles in 50, or 3·6 per cent. Although this method depends upon the measurement of a small difference between two comparatively large quantities, which is a procedure to be avoided in most cases, the accuracy is satisfactory,

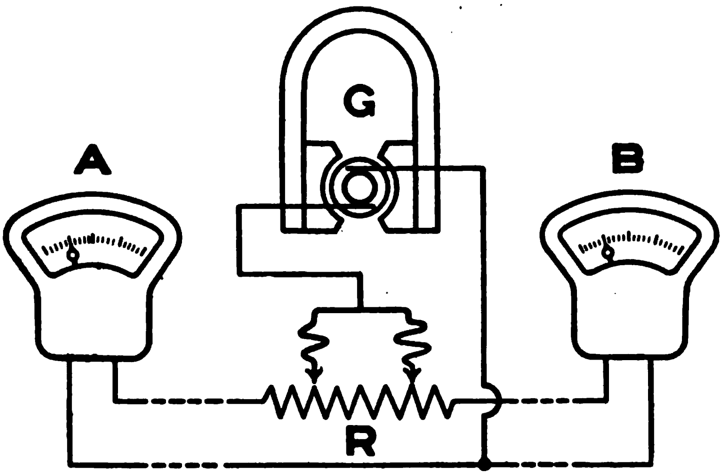


FIG. 231.—Tramcar Speed Indicators.

since the modern vibrating reed frequency meter is an instrument of considerable precision (see p. 269).

Mechanical impulses can be imparted to a vibrating reed frequency meter by means of a toothed wheel attached to the rotating shaft, or in the case of turbines, petrol engines, and other high speed machinery the vibration itself is enough to set a particular reed in resonant vibration. In fact, such mechanical vibrators are very convenient, and are largely used at the present time.

For a description of graphic speed indicators see p. 364.

The electrical speed indicator has proved extremely useful for **tramway and railway work** owing to the serious defects of flexible shafts where long lengths are involved. The treatment meted out to speed indicators used for this

work is such that only the most robust arrangement can withstand it, and the mechanical tachometer has proved quite unsuitable.

Fig. 231 gives a diagram of connections for a set consisting of generator, G, and two indicators, A and B, one for each end of the car. These instruments are connected in parallel across the generator terminals. An adjustable resistance, R, is interposed in each circuit, and by its aid allowance can be made for—

(1) The diameter of the car wheel, which varies greatly in practice owing to wear.

(2) Any weakening of the generator magnet through vibration, etc.

(3) Any variation in the indicator, whether through weakening of the magnet or otherwise.

Oscillographs and other Wave Form Indicators.

The methods employed for this purpose may be divided into two groups. For a continually recurring wave, such as that in an alternating current circuit, a point-by-point curve tracer may be employed, but for a transient wave, and for general application, an oscillograph is essential.

Curve Tracers.

The earliest attempts in this direction were made by **Joubert,** who in 1881 succeeded in plotting the E.M.F. wave of an alternator. He employed a rotating contact attached to the shaft of the alternator and so arranged as to charge up a condenser instantaneously from the supply E.M.F. and then to discharge it through a galvanometer. The device as improved by **Blondel** is shown diagrammatically in Fig. 232. The disc *d*, of insulating material, is fixed to the spindle of the alternator whose wave form is to be traced. It carries a metal drum, against which rests the spring brush b_1. It also has let into it a metal arm, *a*, which makes contact successively with b_2 and b_3 as the disc revolves. Thus the condenser C (usually about $\frac{1}{2}$ mf. in capacity) is placed in

contact first with b_2 and then with b_3. The terminals T_1 and T_2 are connected to the source of supply, so that the condenser receives a charge once in every revolution through the brush b_2, and is in turn discharged through the galvanometer G when the rotating contact passes b_3.

The potential to which the condenser is charged depends upon the point on the E.M.F. wave of the alternator at which contact is made with b_2; and, as the discharges occur in

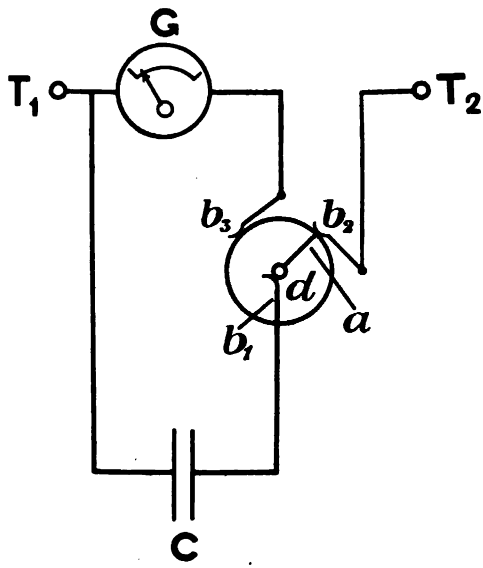


FIG. 232.—Blondel-Joubert Curve Tracer.

rapid succession, the galvanometer receives a unidirectional current and takes up a steady deflection depending upon the mean value of this current. The position of the brushes b_2 and b_3 may be moved round the periphery of the disc *d*, so that the curve of E.M.F. can be explored throughout a whole cycle. The arrangement as outlined is suitable for bipolar machines. In the case of multipolar alternators the disc *d* may either be connected to the shaft through gearing so as to make one contact per cycle, or alternatively the

contact arm *a* may be repeated for each pair of poles on the alternator.

In another arrangement the galvanometer is replaced by an electrostatic voltmeter in parallel with the condenser, and in this manner only two contacts are required, and these do not carry any current. Blondel moved forward the contact by a clockwork mechanism, which also drove a band of sensitised paper on which was reflected a spot of light from the mirror of the galvanometer G, the curve being thereby traced quite automatically.

Hospitalier in his "**ondographe**" employs the same principle, except that he moves the contacts slowly forward by reduction gearing from the disc. This arrangement has the advantage of making the records exactly repeatable, so that curves of current and E.M.F., for example, can be taken one after the other and subsequently superposed. The working forces of the moving coil galvanometer in his arrangement are so great that it is possible to employ a pen to trace the curve.

In many cases it is inconvenient to drive the disc from the alternator itself, and a synchronous motor is then employed, but the angular velocity throughout the revolution must be perfectly even, or the curves will be distorted.

Oscillographs.

These instruments consist of a galvanometer characterised by—

(*a*) A polarised movement so as to show the direction as well as the magnitude of the current or pressure.

(*b*) Extremely light moving parts coupled with relatively large working forces, resulting in a very short natural period of vibration.[1]

(*c*) Critical damping.

In addition, means must be provided for indicating or recording the curves.

[1] The $\dfrac{\text{frequency of current}}{\text{natural period of vibration of system}}$ should never be more than 1/30, and 1/50 is preferable with distorted waves.

Oscillographs are mainly of three types :—

(1) Moving iron.

(2) Moving coil.

(3) Hot wire.

The **moving iron pattern** developed by **Blondel** is similar in principle to the early ammeter used by Ayrton and Perry,[1] and has a strong permanent field in which is stretched a thin strip of steel under considerable tension. The steel is placed so that the lines of force pass along its width. Two coils connected in series, and carrying the current to be investigated, are placed one in front and the other behind the pole tips so as to produce a field at right angles to that due to the permanent magnet. The strip thus tends to set itself with its width along the resultant field, being deflected more or less one way or the other according to the strength and direction of the current.

The momentum of the moving system is so small compared with the control that its free period of vibration is extremely short (about $\frac{1}{30000}$ second). The strip has a minute mirror attached to its centre, and is critically damped (see p. 38) by immersion in a glass tube filled with castor oil.

With this arrangement the deflection of the mirror will accurately follow the wave form for frequencies up to about 1,000 cycles per second.

The **moving coil** or **D'Arsonval** principle was also first suggested by Blondel, but its successful development is due almost entirely to **Duddell**. The principle of action may be seen by reference to Fig. 233. In the narrow gap of a strong permanent or electro-magnet, M, a strip of phosphor bronze is stretched over a pulley. The current to be investigated passes in at T, up S_1, down S_2, and out at T. Thus one strip is urged forward and the other back, so that the mirror *m*, attached to their centres, is deflected through a small angle. The strips are maintained under considerable and equal tensions by the spring C, and in this way a controlling force is provided. The angular deflection, being

[1] See p. 391.

extremely small, is practically proportional to the current flowing, and the motion is damped by immersing the strips in a bath of oil.

When a source of continuous current is available, the electro-magnetic pattern possesses the advantage of greater sensitiveness. On the other hand, for use on high tension circuits without the intervention of transformers the permanent magnet form is to be preferred, on account of the ease with which it can be insulated.

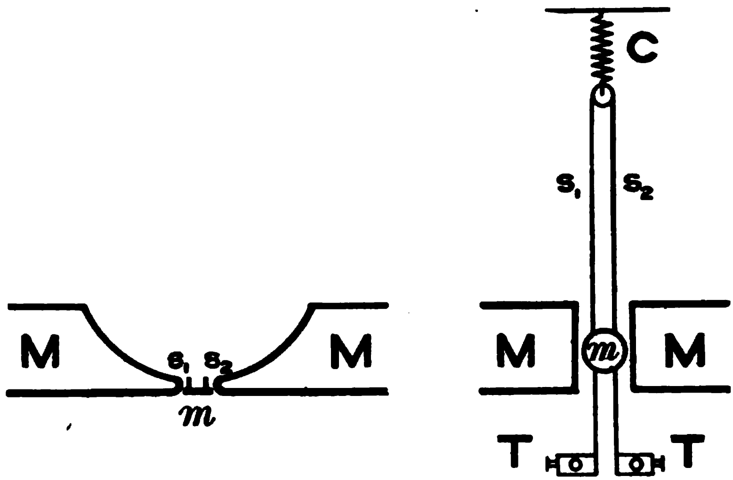


FIG. 233.—Duddell Oscillograph.

The natural period of vibration of the electro-magnetic pattern is about $\frac{1}{10000}$ second and of the permanent magnet pattern about $\frac{1}{3000}$ second, the sensitivity at a scale distance of 50 cms. being about 3 cms. for 0·1 ampere flowing in each case. The resistance of the strips is about 5 ohms and the current which they will carry about 0·1 ampere, so that for heavier currents a shunt is employed and for pressure measurements a series resistance.

It is usual to mount two pairs of strips in the magnet gap, the one being used to measure current and the other pressure. By this means simultaneous curves can be obtained. For methods of recording the curves see p. 378.

The absence of appreciable self-induction in the Duddell oscillograph renders it superior to the Blondel moving iron pattern for most purposes. The latter may have a somewhat shorter free periodic time, and for this reason the Duddell instrument is not suitable for frequencies higher than 500 per second, whereas the moving iron pattern can be used up to 1,000 per second. For an extra-high frequency apparatus see p. 380.

One of the latest oscillographs is the **hot wire type due to Irwin.** At first sight it would appear that, owing to its

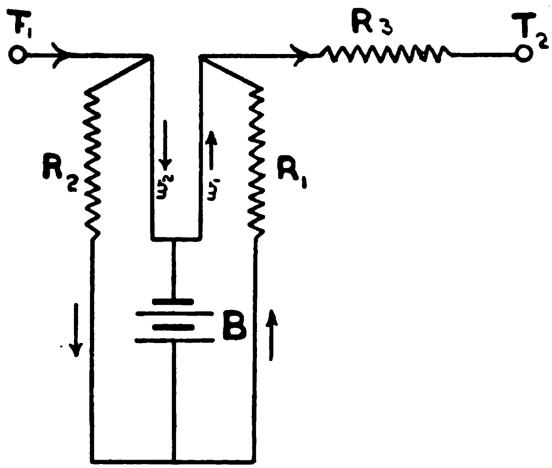


FIG. 234.—Irwin Hot-wire Oscillograph.

sluggishness, a hot wire instrument was singularly ill adapted to the purpose. Irwin has shown, however, that when proper precautions are taken a simple and efficient oscillograph can be so constructed.[1] The first essential is a hot wire galvanometer giving a deflection proportional to the current flowing through it and in a direction dependent upon that of the current. The principle of such a polarised hot wire galvanometer [2] is shown in Fig. 234.

A continuous current from a battery, B, flows up w_1, w_2,

[1] *Proceedings Inst. E.E.*, May 23rd, 1907.
[2] See also p. 237 for a hot wire wattmeter which possesses some points of similarity.

and down R_1, R_2, while the alternating or variable current under investigation flows as shown by the arrows. In this way the wire w_1 carries the sum of the two currents and w_2 their difference, and the extensions will accordingly be proportional to the squares of these quantities. Then, if that part of the alternating current to be measured which flows in w_1 and w_2 is represented by I_a and the continuous current in each of the wires by I_c, the heating and consequently the extension of w_1 will be proportional to $(I_a + I_c)^2$ and that of w_2 to $(I_a - I_c)^2$. Consequently the difference in the extensions of w_1 and w_2 is proportional to $(I_a + I_c)^2 - (I_a - I_c)^2$, that is to $4\ I_a\ I_c$. Thus, if the battery current I_c is constant, the difference in extension will be proportional to I_a and will change sign with it. Hence it follows that if means can be found for making the deflection proportional to the difference in the extensions of w_1 and w_2, a polarised galvanometer giving a deflection proportional to the instantaneous value of the main current will be available. This is arranged for in the Irwin instrument by a simple mechanical coupling between w_1 and w_2. If a high resistance, R_3, is connected as shown in Fig. 234, the deflection will be proportional to the pressure across T_1 and T_2.

In order that the instrument may be employed as an oscillograph, however, some method of overcoming sluggishness is essential. The factors which determine the rapidity with which the temperature of a wire follows any change of current are—

(*a*) The heat capacity of the wire compared with the rate at which heat is generated in it by the current.

(*b*) The rate at which heat is lost by the wire through radiation and convection.

In ordinary hot wire instruments, after taking the utmost care to minimise the effects of both these factors, it is impossible accurately to follow the wave form of an alternating current having a frequency of more than, say, five periods per second. Irwin, however, has devised an ingenious method of accelerating the heating.

In order that the wire may rapidly acquire its final temperature, the current passing through it at each instant should depend upon the rapidity with which the change of temperature has to take place; that is to say, the current flowing should be proportional to the rate of change in the quantity to be measured. Consequently for the measurement of pressure this current should be proportional to the rate at which the potential difference between T_1 and T_2 (Fig. 234) is changing. Now the current which flows into a

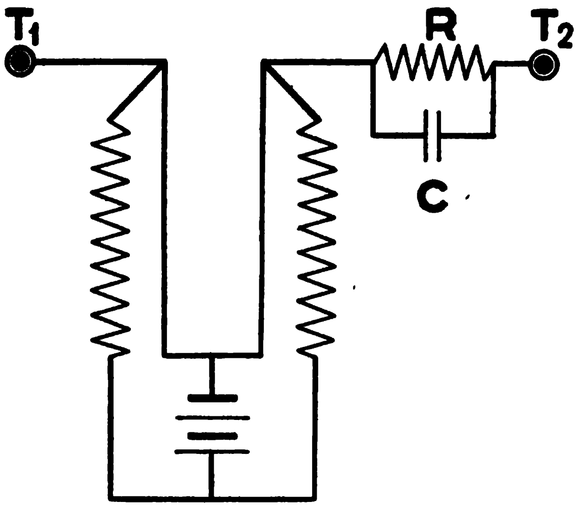


FIG. 235.—Irwin Hot-wire Oscillograph.

condenser exactly meets this requirement, being a maximum when the rate of change of applied pressure is a maximum and zero when the rate of change is zero.

Hence it follows that, neglecting radiation, if the resistance R is replaced by a condenser, the deflection of the mirror will accurately follow the wave of potential difference. In the actual instrument radiation is by no means negligible, and a compromise is necessary. To effect this the condenser C (Fig. 235) is shunted by a resistance, R, the ratio of capacity to resistance being so adjusted as to eliminate sluggishness.

The instrument can also be arranged to measure current. In this case the strips are shunted by an inductive resistance, such a resistance giving a potential difference at its terminals which is proportional to the rate of change of current. By an arrangement similar to that described on p. 237 this oscillograph can be made to indicate power.

Oscillograph Indicating and Recording Mechanism.

All oscillographs employ optical methods of indication, since a pointer or pen-arm would move much too slowly[1] for this purpose.

For **continuously recurring waves,** such as those of an alternating current circuit, the arrangement shown in Fig. 236 is suitable and avoids photography. An arc or other intense source of light, A, sends a beam through the lens L on to the oscillograph mirror M_1, supposed to be capable of vibrating about an axis parallel to the plane of the page. The vibrating ray of light strikes the mirror M_2, and is reflected on to the semi-transparent receiving screen S, where it traces a straight line of light perpendicular to the plane of the page. But the mirror M_2 may also be oscillated about an axis perpendicular to the page, so that the straight line develops into a number of curves, which, owing to the persistence of vision, appear to cross and recross one another. If, however, the oscillations of the mirror M_2 are made to synchronise with those of the oscillograph mirror M_1, the curves representing successive waves will coincide.

In order that the resultant curve may truly represent the wave form, it is essential that the angular velocity of the mirror M_2 shall be constant throughout its travel. This is secured by oscillating the mirror M_2 by means of the specially shaped cam C, driven by a synchronous motor, SM, and against which rests an arm attached to the pivoted mirror. After reaching the end of its travel in one direction the mirror is returned sharply to its starting position by the

[1] As has been seen (p. 372), the periodic time of the oscillograph must be not greater than one-thirtieth that of the current under investigation, and one-fiftieth is better if the wave is very distorted.

arm falling down a steep part of the cam. The curve is only thrown on the screen during the steady forward travel, a rotating shutter, RS, attached to the motor spindle cutting off the light during the return of the mirror by coming between L and M_2. With this arrangement the period of extinction is so short that hardly a flicker is noticeable on the screen.

A convenient form of screen consists of a piece of tracing paper stretched over a sheet of glass. Permanent records may then be obtained by tracing over the curve of light with a pencil. Various forms of synchronous motor are in use for actuating the mirror and shutter, the simplest con-

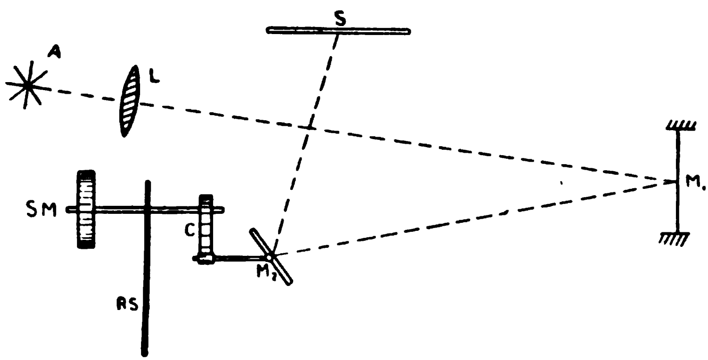


FIG. 236.—Oscillograph Curve-projecting Device.

sisting of a two or four-pole stator, within which rotates an H or double-H armature. It can be started up by means of a winding and commutator, and when once in step the winding may be cut out, and the armature will continue to run as an "attracted iron" motor.

When the phenomenon to be studied is one which **does not give a steady curve over a sufficient period of time** to make the method just described possible (*e.g.* the discharge current of a condenser), recourse must be had to photography for obtaining a record. One of the earliest methods consisted in allowing a sensitised plate to fall by gravity past the position occupied by the screen S in Fig. 236, the mirror M_2 being kept stationary in the

position shown. This arrangement is satisfactory so long as the phenomenon is of short duration, but as the plate is usually arranged to travel at the rate of about half a metre per second, it is clear that for many purposes a much longer record is required than can be obtained on a single photographic plate. As an example may be cited the recording of the surges due to opening a circuit consisting of a long length of cable. For this purpose the falling plate is replaced by a length of cinematograph film, which is driven at a definite speed either by a clock or by an electric motor.

High Frequency Oscillograph.

The Duddell oscillograph may under special circumstances be employed for frequencies up to about 1,000 cycles per

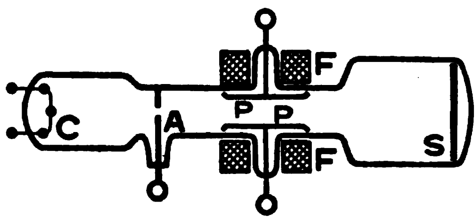


FIG. 237.—High Frequency Oscillograph.

second. Beyond this there is great difficulty in obtaining satisfactory records on account of the weight of the moving parts, and the limit for practical purposes is about 500 cycles per second, since any wave which differs from a true sine curve is sure to contain harmonies of considerably higher frequency. For 300,000 to 1,000,000 cycles per second, as used in radiotelegraphy, some other form of oscillograph is, therefore, essential. For this purpose **Braun** has suggested the use of a cathode ray tube, the ray itself being deflected by electromagnetic and electrostatic forces. Such a tube, as modified by **Wehnelt,** is illustrated in Fig. 237, in which C is the cathode, formed of a strip of platinum heated by a current from a battery.[1] A small spot of lime or of barium oxide

[1] In the simple form due to Braun the cathode was not heated, but the tube then required several thousand volts for the formation of the ray.

on the centre of this strip forms the nucleus of the ray, which passes across the exhausted tube at from 100 to 500 volts. After emerging through a small aperture, A, the ray passes on between a system of potential plates, PP, and field coils, F, until finally it impinges upon a divided fluorescent screen, S, at the end of the tube. If pressure is applied between the potential plates PP, the ray is deflected away from one and towards the other, while excitation of the coils F deflects it in a direction at right angles to this. When both are excited the ray traces a curve on the fluorescent screen which indicates the relationship of pressure and current as regards both phase and magnitude. As the ray possesses no inertia, the apparatus is applicable to all frequencies, but it is not at all easy to use and is only recommended for those cases in which the ordinary oscillograph is useless.

Live Main or Charge Indicators.

In order to give warning when a high tension circuit is alive, instruments based upon the **electrostatic principle**

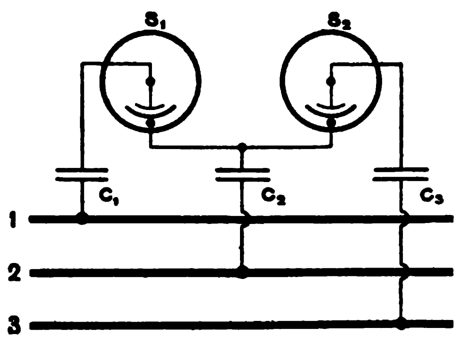


Fig. 238.—Charge Indicators on Three-phase System.

have been introduced. Fig. 238 shows two such applied to an insulated three-phase system. S_1 and S_2 are electrostatic voltmeters of which the scales are coloured half red and half white. Normally, the pointer stands in the white half of the scale, but if the terminals are made alive it

deflects into the red half. The instruments are connected to the lines through condensers, C_1, C_2, and C_3 (see p. 190). Only two voltmeters are required, since even if only one phase is made alive one or both will give a deflection.

Fig. 239 shows a simple form of indicator suitable for attachment to a bare main. A circular ebonite case 4 ins. or 5 ins. in diameter has two fixed plates (A, B) and two movable

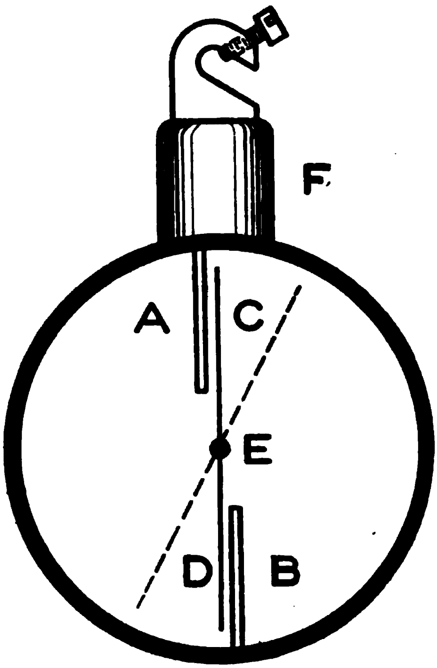


Fig. 239.—Live Main Indicator.

vanes (C, D) pivoted at E. All are in metallic connection with each other and with the main. So long as the latter is dead there is no torque, and, as D is made slightly heavier than C, it hangs vertically downwards. An opaque strip running across the glass (not shown in the figure) hides the movable vane from view until deflected. If the main becomes alive, C and D are repelled by A and B into the position indicated by the dotted lines. To make the deflection more

visible, the edges of C and D may be thickened or bent up and painted red.

Fig. 240 shows a somewhat similar device, but fitted into a porcelain housing, provided with two openings, one at each side, as shown. The letters refer to similar parts to those in Fig. 239. When the main to which they are connected is alive C and D are repelled by B and A respectively, and can be seen through the two openings in the cover.

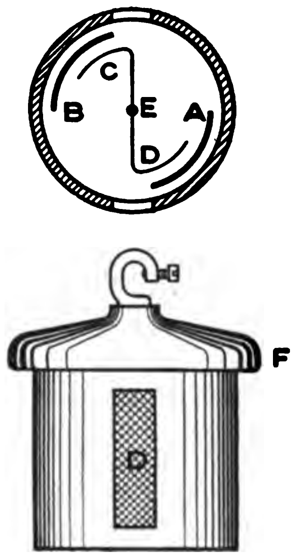


FIG. 240.—Live Main Indicator.

With all such instruments it is essential that the case shall not become charged at the same time as the vanes. If this occurs no deflection will be produced, owing to their being inside a similarly charged conductor. For this reason porcelain insulators, as shown at F (Figs. 239 and 240), are employed. Except in very damp climates, this precaution is quite sufficient; and the instruments are perfectly reliable, and have proved very valuable in preventing accidents. They form a great advance on vacuum tubes and devices of that kind.

Either pattern can be made up in **portable form** with a long insulating handle. In this case a condenser is usually included, so as to insulate the working parts from the live main, and it is advisable to provide an earthing lead which can be connected to earth before use, as an additional precaution.

Earth-plate Testing Sets.

To comply with the **Board of Trade Regulations,** tramway earths should consist of two plates, buried at least 20 yards apart. It is further laid down that they shall

be tested once a month to ensure that "an electromotive force not exceeding 4 volts shall suffice to produce a current of at least 2 amperes " from one plate to the other, or, in other words, that the resistance shall not exceed 2 ohms. All that is required, therefore, for this test is an ammeter reading up to 5 amperes and a 4-volt accumulator.

In central station practice a copper ring main is connected to all the available earthed metal work, such as water-pipes, condensers, etc. A similar test can be applied in this case, but it is usually more convenient to use the supply, so as to pass a reasonably large current, say 100 amperes or more, and to employ a voltmeter of suitable range to measure the drop between the station "earth" and an auxiliary plate carrying no current and buried near by. The resistance of a good station earth should not exceed 0·05 ohm. From a number of tests made by Sparks[1] it would appear that two colliery earth-plates constructed in accordance with the Coal Mines Regulations have an effective resistance while in series of something like 2 ohms in the majority of cases.

An **alternating current bridge** (see p. 97) forms an exceedingly handy apparatus for the purpose of carrying out such tests, since it is unaffected by polarisation. It is not suitable, however, for resistances of less than 0·01 ohm, owing to the difficulty of eliminating contact errors. This apparatus is also useful for testing lightning conductor earths. In the case of these, the resistance of each should preferably be less than 5 ohms and should on no account exceed 10 ohms.

Fig. 241 shows another Wheatstone bridge device which is used to some extent for this work. The slide-wire A forms two arms of the bridge, the other two being represented by the resistance R and the earth-plates E_1 and E_2. Current is supplied by a low voltage alternating current magneto-generator, M. In place of the usual galvanometer, the telephone receiver T is connected through a transformer. The magneto is turned and the position of contact on the slide-

[1] *Journal Inst. E.E.*, Vol. 53, No. 244 (1915).

wire varied until a minimum of sound is heard in the telephone. When balance has been obtained in this way, the resistance of the two earths in series can be read off the direct-reading scale, which is usually graduated to 20 or 50 ohms, often with two ranges. The resistance of each plate is half the value so found for the two in series.

Where only one earth-plate is installed a pair of auxiliary plates must be sunk, temporarily, for the purpose of the test.

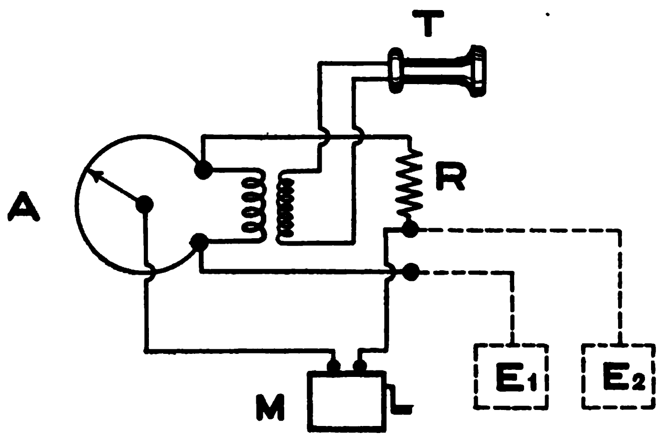


FIG. 241.—Alternating Current Earth-plate Testing Set.

Three resistance measurements are then made as follows :—

From the earth under test to first auxiliary earth (a ohms).
„ „ „ „ second „ „ (b ohms).
„ 1st auxiliary earth to second „ „ (c ohms).

Then, the resistance of the earth-plate under test is:

$$\frac{a + b - c}{2} \text{ ohms.}$$

Rail Bond Testing Sets.

In these instruments a comparison is made between the resistance of the bond and a length of solid rail. For the purpose of the test only the rail current is available, so that

the difficulties are considerable. Fig. 242 shows one of the most satisfactory arrangements, namely the **slide-wire bridge.** The operator carries in one hand the contact-maker (Fig. 243),

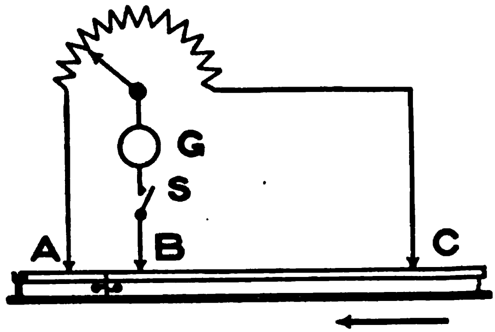


FIG. 242.—Slide-wire Rail Bond Tester.

which is about 4 ft. long and has three contact spikes: A, B, and C. A and C are connected to the slide-wire of a portable Wheatstone bridge (see Fig. 242), while the middle contact is joined to one terminal of the galvanometer

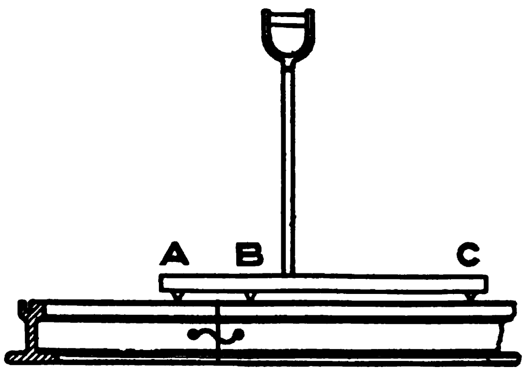


FIG. 243.—Contact-maker for Rail Bond Tester.

G, its other terminal being connected to the slide-wire. To ensure good contact the lathe ABC (Fig. 243) is made springy, and can conveniently be pressed on to the rail by setting a foot upon it. From Fig. 242 it will be seen that the bond (A to B) forms one arm of the bridge, and the length

of solid rail (B to C) another. The position of the slide-wire contact is varied until there is no deflection on closing the switch S, and the equivalent resistance of the bond in terms of so many feet of solid rail can then be read off the scale.

Another arrangement, consisting of **two moving coil instruments**, G_1 and G_2, is shown in Fig. 244. The contact-maker is similar to that shown in Fig. 243, and the deflections on G_1 and G_2 are proportional to the respective resistances of the bond and the length of rail. The ratio of the two readings gives the resistance of the bond. Thus,

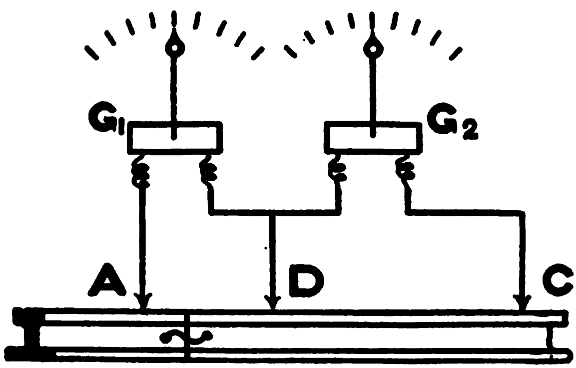


FIG. 244.—Double Instrument Rail Bond Tester.

supposing the length DC to be 4 ft. (which is a very usual value), the resistance of the bond, expressed in feet of solid rail, is—

$$\frac{\text{Reading on } G_1}{\text{Reading on } G_2} \times 4.$$

A variant of this method consists in keeping the contact C separate from the rest and causing a second observer to press it on the rail at various points until one is found which makes the deflection of G_2 equal to that of G_1. The actual distance between D and C when this is the case gives the equivalent resistance of the bond in feet of rail.

Neither of these devices is so satisfactory as that first described, which is direct reading without calculation and does

not entail a second observer. Moreover, fluctuations of current are without effect upon the accuracy. When the current flowing in the rail is abnormally low the last-mentioned arrangement will be found the most sensitive.

Cell-testing Voltmeters.

The chief requirements in these instruments are—

(1) Portability.

(2) Robustness and power of withstanding corrosion.

(3) Rapidity of indication.

(4) Accuracy.

It was at one time customary to fit cell testers in polished wooden cases provided with leather strap handles. Such

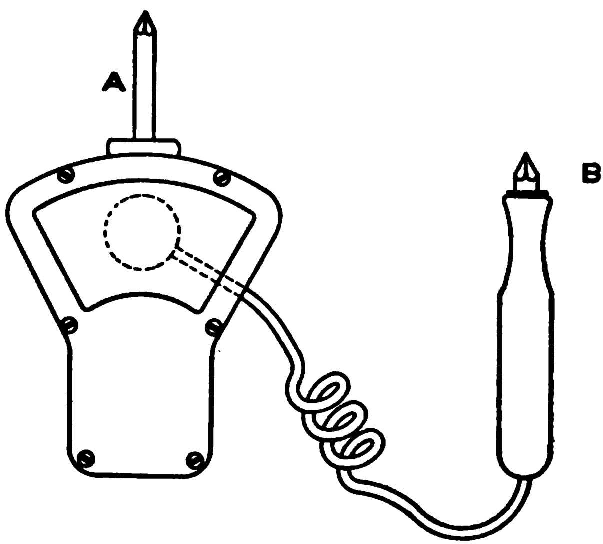


FIG. 245.—Cell-testing Voltmeter.

cases were, however, soon destroyed by the acid, and voltmeters are now usually fitted in **cases of aluminium** or, more rarely, of ebonite. Figs. 245 and 246 show a compact form of aluminium case. The narrow end is rounded off so that it can be comfortably held, and the hand-spikes A and B serve to

make contact with the lugs of the cell. One of these can be screwed into either of two positions, A or C, as may be convenient, while the other, B, is attached to a length of flexible cord, and may take the form of a sharp hook, as shown in Fig. 247 at D.

In some cases a separate "**contact spear**" is preferred, three forms being shown in Fig. 247, which is almost self-explanatory. In the upper figure one of the contacts is adjustable so as to suit various sizes of cell, while in the lower figure a saw-blade contact is employed which can be used with cells of almost any size.

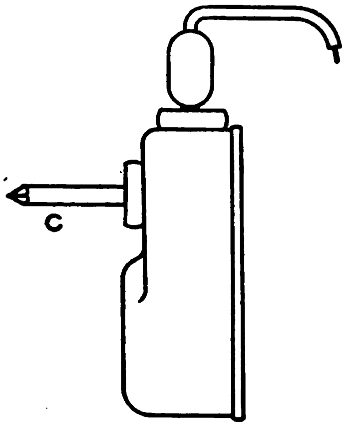


FIG. 246.—Cell-testing Voltmeter.

To fulfil the third requirement, dead-beatness or rather "snappiness" is essential, and since in going round a battery the polarity changes from cell to cell, a central zero

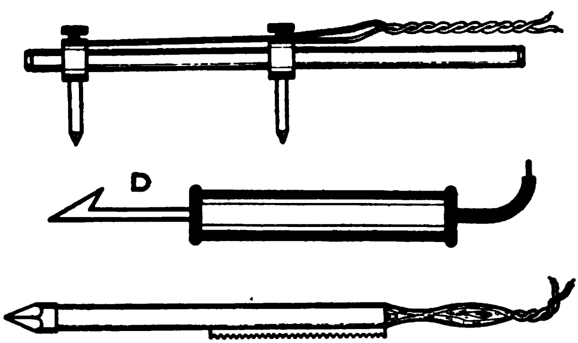


FIG. 247.— Contact Spears for Cell Testing.

voltmeter is convenient. For this reason, and in view of the fourth requirement, a moving coil movement is almost always used.

For many purposes, and particularly for the testing of ignition cells, the open circuit voltage, such as is measured by a high resistance voltmeter, is of less importance than that yielded when **the cell is discharging at its normal rate.** In order that this may readily be measured in the case of small cells, a resistance can be arranged inside the voltmeter case, which is connected, either permanently or by means of a key, across its terminals. In this way the voltage can be measured under actual working conditions, and if a key or plug is provided in the low resistance circuit, so that the open circuit voltage can also be measured, the internal resistance of the cell can be calculated from the formula—

$$R_i = \frac{V_1 - V_2}{V_2} R_x,$$

where V_1 and V_2 are the open and closed circuit readings respectively, while R_i and R_x are the internal (battery) and external (load) resistances, respectively. The value of the latter (namely, that in the voltmeter), say 1 ohm, should be marked on the dial of the instrument.

Motor Car Voltmeters and Ammeters.

The development of the **accumulator-driven car** has led to a demand for instruments of compact design suitable for fixing to the dashboard. They usually consist of a moving coil voltmeter and ammeter fitted in a common brass or aluminium case, according to the finish of the car. A useful design is shown in Fig. 248. In order that the same instruments may be used for charge and discharge currents, the ammeter should be provided with a central or displaced zero, while the voltmeter has a side zero.

Of late years the provision of an **electric battery and charging dynamo on petrol-driven cars** has become the rule, and an ammeter, if not a voltmeter, almost invariably forms part of the equipment. Unfortunately, with a view to economy, the instrument fitted is often of a very inferior kind, and can only be regarded as a rough indicator.

Fig. 249 shows one such instrument, on the lines of that due to Ayrton and Perry—a principle which was abandoned

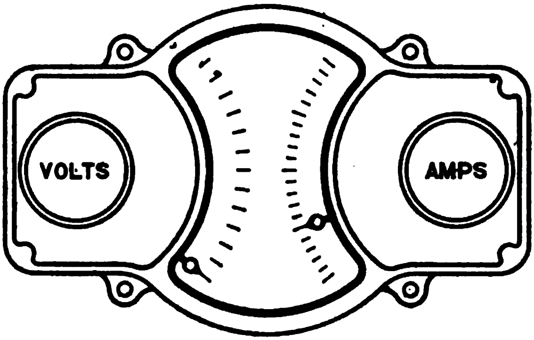


FIG. 248.—Electric Vehicle Dashboard Instrument.

nearly twenty years ago. Between the poles (N, S) of the permanent magnet a soft iron needle is pivoted, which carries the pointer and is polarised by the magnet, as

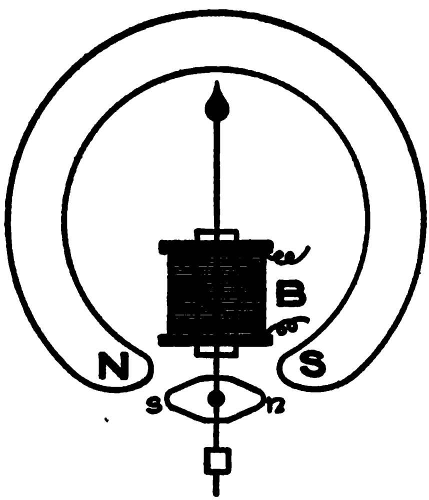


FIG. 249.—Crude Form of Dashboard Ammeter.

shown by *n*, *s*. The current to be measured flows through the coil B. Supposing the direction to be such that the lower end of this coil becomes a north pole, the south end (*s*)

of the needle will be attracted, and the stronger the current the larger will be the deflection. By suitably shaping the poles it is possible to obtain a fairly evenly divided scale, and as the instrument is polarised, it is suitable for measuring the charge and discharge of a battery. The working forces can be made large, which is of importance owing to vibration.

On the other hand, the disadvantages of this pattern are many. Owing to the long air-gap, the magnet is easily weakened, and is sensitive to external magnetic fields. Since the deflection depends upon the strength of the magnet (increasing as this weakens), it follows that little reliance can be placed upon the readings. The instrument is also very inefficient, requiring a high drop as an ammeter and a large current as a voltmeter.

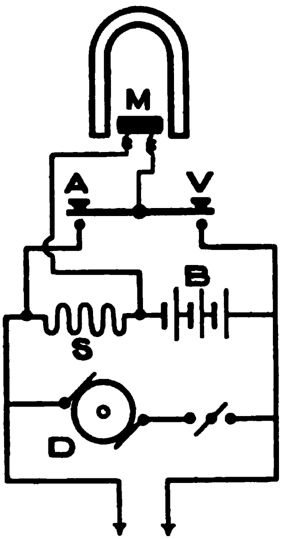


FIG. 250. — Connections for Dashboard Volt-ammeter.

In the better class of lighting sets a **moving coil instrument** is provided, as should always be the case. The best arrangement consists of a central zero ammeter and a side zero voltmeter, preferably in the same case and mounted on a small switchboard. When space is of importance, a combined volt-ammeter can be used, a convenient arrangement being shown in Fig. 250. D represents the charging dynamo, B the battery, while the two-way press switch marked A and V enables the moving coil M to be connected either to the shunt S for current measurements or across the battery for voltage measurements. The voltmeter (or volt scale) often has a red mark to show the minimum permissible voltage before charging is resorted to, or one which shows that the battery is fully charged and can be disconnected from the dynamo.

Voltage and Current Relays.

In the ordinary acceptation of the term, a relay is an apparatus by which a circuit is opened or closed by a current flowing in another circuit. The most used relays are those intended for line or cable protection, but their functions are so specialised that they are not dealt with in the present volume. For the same reason descriptions of the various telephone and telegraph relays are omitted.

There are, however, many other purposes for which voltage and current relays are used, and brief mention must be made of these. Besides the ringing of a bell or the lighting up of a lamp, should the current rise or the pressure fall beyond a predetermined value, such instruments are largely used in connection with automatic lighting plants.

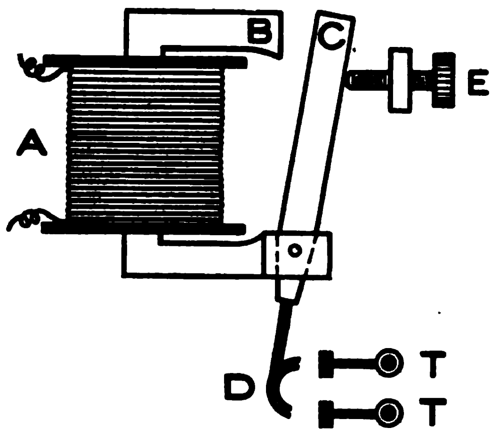


FIG. 251.—Maximum Current Relay.

One form of maximum current (or voltage) relay is shown in Fig. 251. The coil A magnetises the soft iron core B, and so soon as the current exceeds a certain value the armature C is attracted and contact made by the brush D. This closes the auxiliary circuit connected to the terminals TT. The current at which the armature is attracted can be varied by regulating the distance between B and C by means of the screw E.

Such a relay can be used with continuous or alternating current, but is only suitable for rough work, as it cannot be relied upon to within much less than $\pm$ 10 per cent. Fig. 252 shows an improved arrangement of the same kind. The core A is drawn into the coil B; and being rigidly fixed to the bell-crank lever C, pivoted at D, the contact at E is made at a current depending upon the value and position of the adjustable counterweight F. The two fixed contacts (maximum and minimum) consist of discs of platinum mounted on adjusting screws. The moving contact also consists of a platinum wheel capable of being turned round. By this means a fresh contact surface can be presented

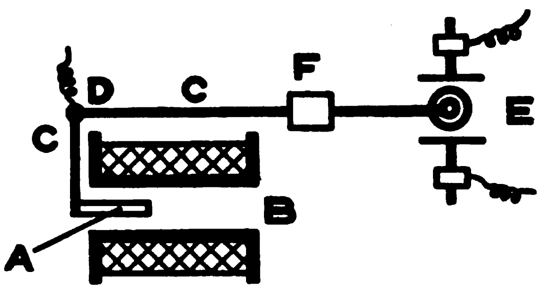


FIG. 252.—Maximum and Minimum Relay.

when it becomes pitted or worn. Such a relay may be adjusted to give reliable indications to within $\pm$ 2 per cent.

For accurate work with **continuous current**, the moving coil principle is by far the most satisfactory, since larger working forces are available for a given expenditure of power, besides possessing various other advantages common to the moving coil system, such as absence of hysteresis, freedom from disturbance by stray magnetic fields, ease with which any desired range can be obtained, and so forth.

Fig. 253 shows the **contact-making portion** of such an instrument (Everett, Edgcumb). A is the moving coil, the magnet, pole pieces, and core being omitted for the sake of clearness. Attached to this coil is a pointer which carries a platinum contact, B, so arranged as to be capable of touching

either of two similar contacts, C and D, attached to a pair of adjustable arms carrying pointers. These arms are capable of being swung round the same centre as the moving coil, and can be clamped in any desired position on the scale. The contacts attached to them are so arranged that when the pointer carried by the moving coil coincides with one or other of the two adjustable pointers, the circuit is closed. Current is led

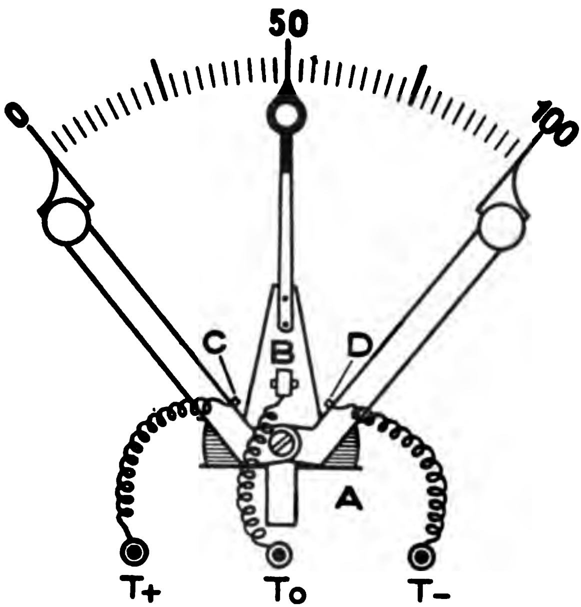


FIG. 253.—Maximum and Minimum Moving Coil Relay.

to the contacts by flexible leads from the respective terminals T_+, T_0, and $T-$. The relay shown can be used to close the circuit both when the current (or voltage) is too high and too low. If it is only wished to deal with the one or the other condition the second contact arm can be omitted.

For use with **alternating current** either an induction movement (p. 166) or, better, an iron-cored dynamometer (see p. 219) can be employed.

For the **contacts**, platinum is the most satisfactory material, although silver has some advantages when the working

forces are exceptionally low. This metal should never be used, however, for any but the smallest currents. Tungsten has low price to recommend it, and gives good results, provided the working forces are adequate. Alloys of palladium (6 per cent.) and silver have also been tried. It will usually be found best to fix the contacts at a comparatively short radius, as shown in Fig. 253. By so doing the pressure is increased, although the break becomes

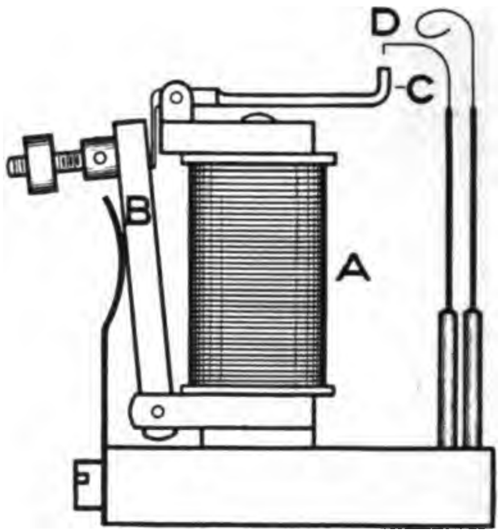


Fig. 254.—Sensitive Relay.

shorter in proportion and accurate setting more difficult to attain. Fig. 252 may be contrasted in this connection.

As regards the **current which can safely be carried** by such contacts, this depends upon the conditions of each case. If the greatest possible accuracy is desired, the current should not exceed $\frac{1}{20}$ ampere at 20 or 30 volts, but as much as $\frac{1}{5}$ ampere at 250 volts (or a correspondingly increased current at a lower voltage) can be dealt with if a less accurate setting is sufficient, and if the circuit is never broken at the contacts. Under no circumstances should the current be more than 2 or 3 amperes. For currents exceeding these limits

mercury cups and steel contact points can be used, but an accuracy greater than 2 per cent. or 3 per cent. is then difficult to attain. In a general way, it may be said that about 20 volts will be found a **satisfactory voltage** to use. A lower pressure is liable to give uncertain contact, and a higher pressure leads to excessive sparking. A condenser connected across the break is effective in suppressing sparking and consequent burning of the contacts.

A very **sensitive form of relay** has been devised by Paul for use with instruments in which the working forces are too small to allow of direct action. It is shown in Fig. 254. The electro-magnet A is energised at short intervals, say every half-minute, and when this occurs the armature B presses up the bell-crank lever, terminating in a fork, C, which passes on either side of the two contacts D. The position of the relay is such that when deflected the pointer of the galvanometer or other instrument passes between C and the lower contact D. When exactly over C, it is carried up by it, and forces the contacts D together, thus closing the local circuit. The intermittent current for the magnet A can be provided by means of a clock-driven contact or by means of the device described on p. 356.

Measurement of the Starting Current of a Motor.

It is not easy with an ordinary instrument, unless it is exceptionally "snappy," to measure the maximum current taken by a motor in starting. This is, however, a measurement which is often valuable; and a very simple attachment enables it to be made. It consists in an **adjustable stop** which, by means of a milled knob, can be used to push the index up to any desired point on the scale. As an example, suppose the starting current is expected to be about 50 amperes; the pointer would be moved up to, say, the 45-ampere reading. If on starting the pointer left the stop, it would show that the current exceeded 45 amperes, and by moving it further up and repeating the test the actual current can be determined within very narrow limits.

This arrangement proves of use for a number of purposes besides the measurement of starting currents. For example, the current taken to reverse a planing machine or to drive a rolling mill is easily measured in this way.

It is sometimes sought to measure transient maximum currents of this kind by means of a **loose non-return pointer,** which is carried forward by a projection from the pointer proper and remains at the maximum point reached. Such devices are extremely unsatisfactory owing to the friction they introduce and also to the "overshoot" due to the momentum of the moving parts. Moreover, if subjected to vibration the loose pointer is liable to shift of its own accord.

Paralleling Voltmeters.

Before a generator, whether continuous or alternating current, is connected to the bus-bars, it is essential that—

(1) Its polarity should be correct.

(2) Its terminal voltage should be the same as that of the bars.

In the case of an alternating current generator it is also essential that—

(3) The frequency and phase should be the same.

The third requirement is dealt with by a synchroniser (see p. 279), and the "paralleling voltmeter" is only concerned with the voltage and polarity.

For a **continuous current** circuit a displaced zero moving coil voltmeter may be employed, so connected across the open contacts of the main switch that when the voltage and polarity are correct the reading is zero. Considerable sensitiveness is essential at or near the zero point, in order that the generator pressure may be adjusted to a nicety. To this end a press-key is often provided, by means of which the range can be reduced to one-tenth, when the generator pressure is nearly correct.

It is customary to provide such a voltmeter with a zero in the centre of the scale. This is unnecessary, since the polarity of the bus-bars never changes, and the effective

length of scale is thereby reduced to one-half. It is quite sufficient for the scale to be carried some 10 per cent. or so to the left of the zero point. For example, an instrument intended for a 220-volt plant would often be scaled 250–0–250, but better 25–0–250 volts, and, with the key depressed, 2·5–0–25 volts.

An alternative, although less satisfactory, arrangement consists in a second spring, which only comes into play when the deflection exceeds a predetermined value, say 25 volts in the above-cited case. In this way 25 volts will carry the pointer to perhaps the middle of the scale, while a further 225 volts carries it to the end. A disadvantage of this arrangement is that either the control due to the 25-volt spring must be excessively small, or else the power consumption at 220 volts will be considerable and the heat generated difficult to dissipate.

A convenient form of **portable paralleling voltmeter** is shown in Fig. 255. On a large switchboard it is often difficult to find a point at which to place the voltmeter so that it may be clearly seen from all the machine panels, and it is then convenient to have a portable instrument which can be carried to any panel and plugged into sockets provided for the purpose. The range-changing key is shown at A, this position being chosen with a view to obviating the risk of its being accidentally closed before the voltage adjustment is sufficiently close.

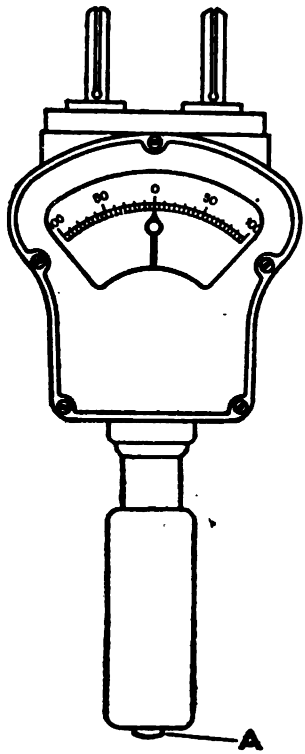


FIG. 255.—Continuous Current Paralleling Voltmeter.

If the generator is connected to the bars through two

single pole switches, it is sufficient to close one pole first and to join the voltmeter across the open gaps on the other pole. If, as is almost invariably the case, the switch is double pole, this cannot be done and the paralleling voltmeter is then

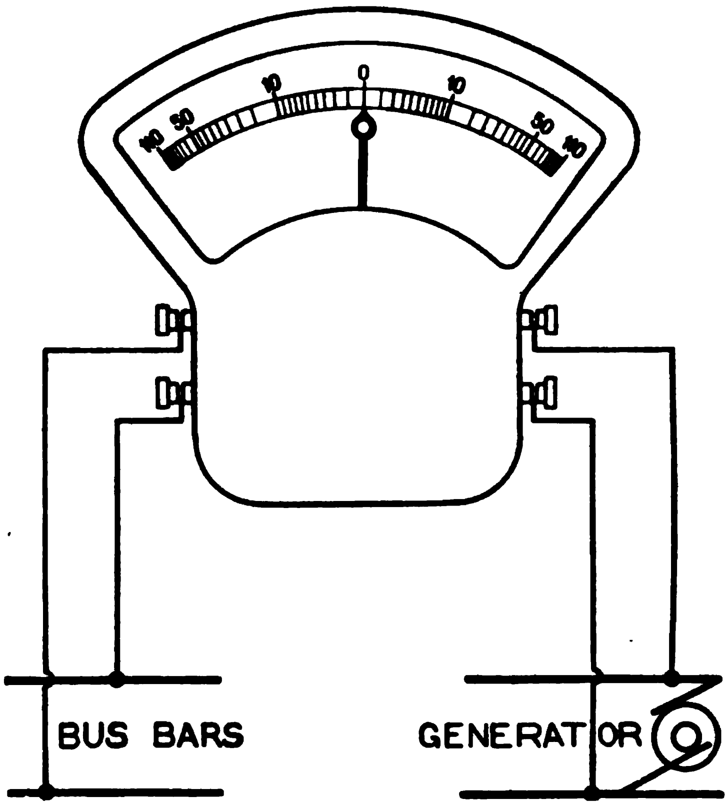


FIG. 256.—The "Paller" Alternating Current Paralleling Voltmeter.

provided with four prongs, two of which short-circuit one pair of contacts on the switch while the others throw the voltmeter across the remaining pair. Failing this, an incandescent lamp can be connected across one pair of contacts and the voltmeter across the other pair. The resistance of the lamp is so low compared with that of the instrument that the accuracy of the latter is not thereby impaired.

In the case of an **alternating current** station an instrument of this kind is more difficult to devise, since the conditions are fundamentally different, and, moreover, the scale near the zero point is always very cramped (see p. 139). An instrument has recently been introduced by Everett-Edgcumbe, known as the "Paller," in which this difficulty has been overcome. It consists of a double "universal" movement (as shown in Fig. 79), one coil being connected through a resistance across the bus-bars and the other across the incoming generator (Fig. 256). When the voltages are equal the pointer stands at zero, deflecting to the right or left according to which of the two is the higher. By this means the scale is precisely of the form required, namely, very open on either side of zero and closed up towards the ends, as will be seen from Fig. 256.

It may be pointed out that this arrangement is equally applicable to continuous current systems and may take the form of a moving coil instrument with two distinct windings on the moving coil. Insulation difficulties are liable to arise, however, and the more usual single pole arrangement with displaced zero, as already described, is to be preferred.

Compensated Voltmeters.

An essential condition in the distribution of electrical energy on a public supply system is that the voltage shall remain as nearly constant as possible, not so much at the station bus-bars as at the terminals of the consumer's lamps or motors.

For this reason station voltmeters are often so arranged as to read the pressure at the end of the feeders by means of pilot wires running back from the distributing centres to them. Such pilot wires form, however, a clumsy and expensive arrangement, and are unnecessary if the voltmeters are "compensated" for the drop in volts between the station and the distributing centre.

Generally speaking, the principle adopted is that of a **double-wound instrument,** in which one winding is connected as a voltmeter, in the usual manner, across the bus-

bars. This winding provides the deflecting force, and if the instrument is operated solely by it, the reading obtained will be the voltage of the bus-bars. The other winding is in series with the line, and causes the instrument to act as an ammeter.

Now the drop in the feeder is proportional to the current flowing and to the resistance or impedance of the feeder. By adopting correct proportionality between the two windings, the reading, when current is flowing through the "ammeter" winding alone, depends upon the voltage drop

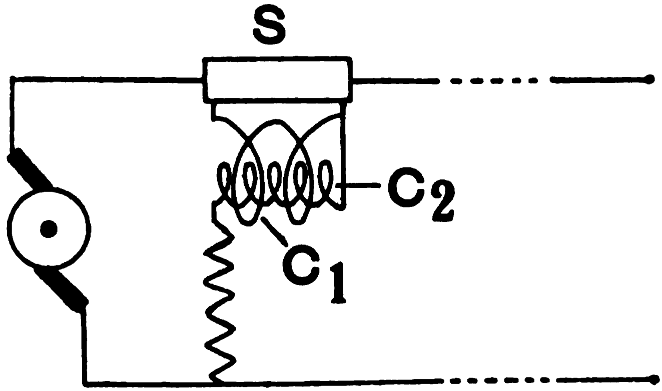


FIG. 257.—Continuous Current Compensated Voltmeter.

in the feeder. The connections are so arranged that for outgoing currents the two windings are in opposition, so that the reading obtained corresponds to the bus-bar voltage less the drop in the feeder, that is, to the voltage at the distributing centre.

The arrangement as applied to a continuous current system is shown diagrammatically in Fig. 257, in which C_1 is the "ammeter" winding, operated from the shunt S. The "voltmeter" element consists of the winding C_2, connected in series with a high resistance. In practice, for continuous currents a moving coil instrument is usually employed, the two windings being either on one former or on two separate formers attached to the same spindle.

The device is also applicable to **alternating current** circuits, and can be arranged either with direct connected windings or to be operated through pressure and current transformers. It should be observed that in compensating for the reactance drop in an alternating current feeder this component is in quadrature with the current. For this reason it is only possible to compensate accurately for one definite power factor, but in practice there is no difficulty in obtaining sufficiently consistent results.

In the case of a **three-wire continuous current** system two instruments, each with three windings, are required, as shown in Fig. 258. The voltmeter coils VC_1 and VC_2 are connected in the ordinary way, and the compensating windings C_1, C_2, and C_3 are joined to the shunts S_1, S_2, and S_3 respectively. The drop in the outers is measured as already described, while that in the middle wire is automatically added or subtracted, according to the direction of the current in it. A **five-wire system** can be dealt with in the same way by the use of four triple instruments similarly connected up.

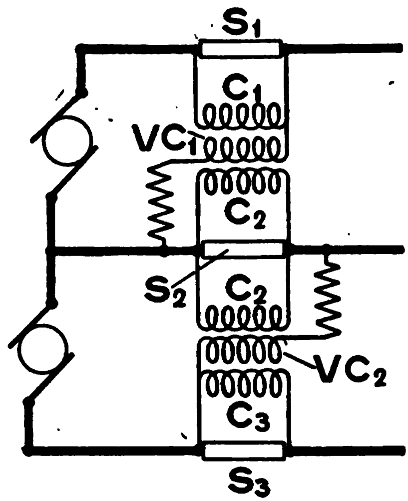


FIG. 258.—Continuous Current Three-wire Compensated Voltmeter.

Bohle has shown[1] that it is possible to measure the **average pressure at a number of feeding points,** the connections for a two-wire system being given in Fig. 259. S_1, S_2, and S_3 represent shunts, one being connected in each feeder. A number of equal resistances, R, are connected from one end of each of the shunts to a common point, which thus

[1] *Electrician*, Vol. 75, p. 501 (1915).

takes up the average potential of the outer shunt ends. The coil C, accordingly, receives a current proportional to the average drop in the feeders, and the reading due to VC is proportionately reduced. On a three-wire system a shunt is inserted in the middle wire, as shown in Fig. 258, the connections remaining otherwise as in Fig. 259.

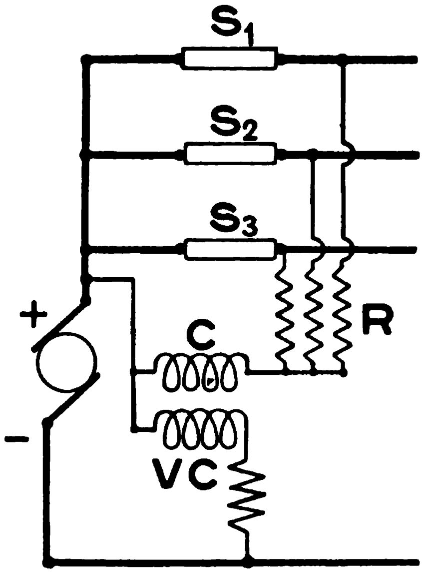


FIG. 259.—Continuous Current Voltmeter compensated for Average Feeder Drop.

In all these devices **insulation difficulties** arise, particularly with moving coil instruments. On two-wire systems no considerable difference of potential exists between windings, but with three wires it is preferable to use a separate movement for C_2, attached to a common spindle, since it is easier to insulate two movements from one another than two windings on one former. Changes of feeder resistance with temperature also detract from the accuracy.

Crest or Peak Voltmeters.

Dielectric stresses are dependent upon the maximum or "crest" value, rather than upon the R.M.S. value of the applied pressure. Consequently methods have been devised for measuring this directly. One such (due to Sharp and **contact-maker** (see p. 370) connected to an electrostatic Farmer) consists in a synchronously driven **Joubert** voltmeter. The contact is moved round until a maximum reading is obtained, and this corresponds to the crest value.

Another device consists of an **oscillograph** (p. 372)

without motor-driven mirror.[1] A band of light is thus obtained on the screen, the length of which is a measure of the crest value. As the spot of light is stationary at the end of its travel, this point is sharply defined by the increased intensity of the illumination. Only half the band is exposed to view, since the deflection is symmetrical on either side of zero.

Sharp and Doyle[2] propose the arrangement shown in Fig. 260. The pressure to be measured is applied by means of the terminals TT to the electrostatic voltmeter V through the **electric valve** A. This valve may be an ionic discharge-

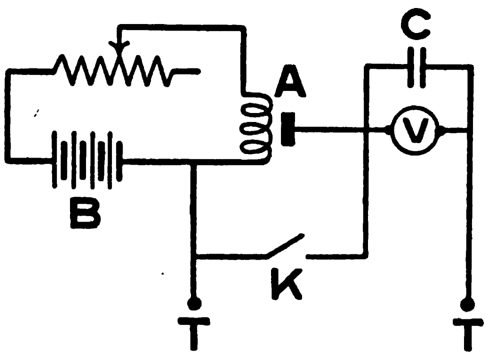


FIG. 260.—Electric Valve Crest Voltmeter.

tube of Langmuir, which thus charges the voltmeter and the condenser C connected across its terminals to the crest value. The cathode may be heated either by a battery, as shown in the figure, or by an alternating current if preferred. The key K enables the R.M.S. value to be determined, should this be desired, by cutting out the valve. Instead of the electrostatic voltmeter a galvanometer in series with a very high resistance can be employed.

When using a crest voltmeter for cable-testing, it must be remembered that the corresponding sinusoidal test pressure (R.M.S.) will be—

$$\frac{\text{Crest voltmeter reading}}{\sqrt{2}}$$

[1] See Middleton and Davies, *Proc. Am. Inst. E.E.*, Vol. 33, p. 987.
[2] *Proc. Am. Inst. E.E.*, Vol. 35, p. 129 (1916).

INDEX

INDEX

WHITEFRIARS PRESS, LTD., LONDON AND TONBRIDGE.